Grounded Learning Experience:
Helping Students Learn Physics through Visuo-Haptic Priming and Instruction

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ABSTRACT

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In this dissertation, I investigate the effects of a grounded learning experience on college students' mental models of physics systems. The grounded learning experience consisted of a priming stage and an instruction stage, and within each stage, one of two different types of visuo-haptic representation was applied: visuo-gestural simulation (visual modality and gestures) and visuo-haptic simulation (visual modality, gestures, and somatosensory information).

A pilot study involving N = 23 college students examined how using different types of visuo-haptic representation in instruction affected people's mental model construction for physics systems. Participants' abilities to construct mental models were operationalized through their pretest-to-posttest gain scores for a basic physics system and their performance on a transfer task involving an advanced physics system. Findings from this pilot study revealed that, while both simulations significantly improved participants' mental modal construction for physics systems, visuo-haptic simulation was significantly better than visuo-gestural simulation. In addition, clinical interviews suggested that participants' mental model construction for physics systems benefited from receiving visuo-haptic simulation in a tutorial prior to the instruction stage.

A dissertation study involving N = 96 college students examined how types of visuo-haptic representation in different applications support participants' mental model construction for physics systems. Participant's abilities to construct mental models were again operationalized through their pretest-to-posttest gain scores for a basic physics system and their performance on a transfer task involving an advanced physics system. Participants' physics misconceptions were also measured before and after the grounded learning experience. Findings from this dissertation study not only revealed that visuo-haptic simulation was significantly more effective in promoting mental model construction and remedying participants' physics misconceptions than visuo-gestural simulation, they also revealed that visuo-haptic simulation was more effective during the priming stage than during the instruction stage. Interestingly, the effects of visuo-haptic simulation in priming and visuo-haptic simulation in instruction on participants' pretest-to-posttest gain scores for a basic physics system appeared additive. These results suggested that visuo-haptic simulation is effective in physics learning, especially when it is used during the priming stage.

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Chapter I

INTRODUCTION

The Role of Visuo-Haptic Representation in Mental Model Construction

The overarching objective of this dissertation is to understand how to better help people learn about systems. A system is a collection of interrelated concepts that, when considered together, performs certain functions. The goal for this dissertation is to provide people with a learning experience that promotes their knowledge of systems through constructing mental models with visuo-haptic priming and instruction.

Cognitive psychologists have long suggested that experiential learning is superior to behavioral learning in obtaining new knowledge (Bruner, 1966; Kolb, 1984; Piaget, 1970). During experiential learning, people gradually understand the world that surrounds them through observation. The knowledge formed from this process is called mental models, which are internal representations of external systems (Gentner & Stevens, 1983). With mental models, people gain a deep understanding of systems in both real and imaginary situations (Seel & Strittmatter, 1989). In addition, people can manipulate their mental models to predict unobserved events and transfer their existing understanding of one system to other systems (Chan & Black, 2006)

In order to apply mental models in learning, it is essential to understand how mental models are formed. The cognitive processes behind mental model formation are called mental model construction. Depending on the activation of relevant prior experiences, mental models are constructed through either model formation or people's interactions with external systems. When observing an external system without activating relevant prior experiences, a mental model of such a system is constructed through establishing a chain of observed causal relations that simultaneously connect all entities within a domain (de Kleer & Brown, 1983). However, simultaneously processing these complex causal relations poses a heavy demand on people's already limited working memory capacity. Therefore, finding a better way to process these complex causal relations is essential to mental model construction.

Alternatively, Norman (1983) proposed that people construct mental models through the interaction between their relevant prior experiences and external systems. From this perspective, people constantly compare their relevant prior experiences to external systems. Based upon this comparison, people continue to modify their mental models until the models are workable for learning the external systems. With relevant prior experiences activated, people can expedite mental model construction and achieve better learning in a shorter period of time. However, people often do not explicitly refer their learning of a new external system to their prior experience. Even when they do, they often have difficulties in determining which of their prior experiences is the most relevant to the external system. Therefore, finding a better way to help people activate the relevant prior experiences during the learning process is important in promoting mental model construction.

Causal relations processing and relevant prior experience activation pose constraints in mental model construction, which can be further understood through cognitive load theory (see Sweller & Chandler, 1994). When causal relations in a given external system are presented in a manner that is hard for people to process, people's working memory is burdened with unnecessary information called the extraneous cognitive load. When the extraneous cognitive load is high, people need to process it using their limited cognitive resource first before they can process causal relations in the external system. As a result, the increased extraneous cognitive load limits people's abilities to construct mental models. Similarly, when relevant prior experiences are not activated, people spend more time construing mental models with model formation. As a result, people obtain less knowledge, or the germane cognitive load, and are thus unable to achieve better learning within a limited period of time. Therefore, providing people with a learning experience that can reduce the extraneous cognitive load and promote the germane cognitive load is crucial to mental model construction.

Findings from grounded cognition and multimodal representation suggest that reducing the extraneous cognitive load and promoting the germane cognitive load can be better achieved through visuo-haptic representation. Two types of visuo-haptic representation exist: visuo-gestural simulation and visuo-haptic simulation. In the past, visuo-haptic representation has often been accomplished by incorporating the visual modality and gestures. This type of visuo-haptic representation is understood here as visuo-gestural simulation. Alternatively, adding somatosensory information to gestures provides a more comprehensive haptic representation that facilitates people's abilities to construct mental models. Therefore, this research is based on visuo-haptic simulation, a type of visuo-haptic representation that incorporates the visual modality, gestures, and somatosensory information. Within the research for this dissertation, somatosensory information is achieved through providing a force feedback to the haptic channel.

I maintained that visuo-haptic simulation is superior to visuo-gestural simulation for mental model construction because it provides people with a more realistic and interactive experience that reduces the extraneous cognitive load and promotes the germane cognitive load. To understand the benefits of visuo-haptic simulation, I examine both types of visuo-haptic representation in two different types of application: priming and instruction. I argue that when a visuo-haptic simulation is used during instruction, people "off-load" processing demands from the visual modality to the haptic modality. Off-loading processing demands to the haptic modality reduces people's extraneous cognitive load because it facilitates processing demands in the visual modality so that people use less effort to learn the external systems. Alternatively, when a visuo-haptic simulation is used before instruction (i.e. priming), people's relevant prior experiences are activated to interact with the external systems and promote the germane cognitive load. In addition, activated relevant prior experiences provide cues for people to "weed out" unnecessary information in later instruction and reduce the extraneous cognitive load.

To examine both types of visuo-haptic representation in both types of application in mental model construction, I use physics as the content subject in this dissertation. Physics is employed in this dissertation because people have varied levels of prior experience with physics systems that can be activated during the learning process, and concepts in physics systems can be simulated through both types of visuo-haptic representation. In practice, experiential learning has also been strongly emphasized in learning physics systems. It is suggested that people achieve better conceptual understandings of physics systems when such systems are experientially learned. In fact, many science educators advocate for this type of learning for conceptual physics because it promotes deep and fundamental understanding of physics through observing experiments, labs, demonstrations, and visualizations (Forbus, 1997; Furio & Guisasola, 1998; Hewitt, 2002). Nevertheless, physics systems can be too abstract for people to find relevant prior experiences and too complex to process. In other words, people often encounter previously mentioned constraints in mental model construction when they attempt to learn physics systems conceptually. In short, physics systems are an ideal candidate for this dissertation because people have prior experiences in physics systems, they are suitable for visuo-haptic representations, and they demonstrate previously mentioned constraints in mental model construction.

Overview of the Dissertation

This dissertation is organized into five chapters. Chapter II provides a review of the literature relevant to this research. Discussions of existing works in these areas provide the foundation to the grounded learning experience framework proposed. In addition, Chapter II describes the design of a catapult simulation that accommodates both types of visuo-haptic representation in the empirical studies of this research.

Chapter III presents a pilot study that investigated how types of visuo-haptic representation in instruction affect people's ability to construct a mental model for a physics system. In this pilot study, I differentiated abilities in constructing mental models for physics systems by comparing two groups of participants, separated by types of visuo-haptic representation received in instruction, in their problem-solving ability on a basic physics system and their transfer performances on an advanced physics system.

Chapter IV presents a dissertation study that extended the pilot study. In this dissertation study, I investigated how types of visuo-haptic representation in different applications affect people's abilities to construct mental models for physics systems by comparing four groups of participants, separated by types of visuo-haptic representation received in priming and instruction, in their problem-solving ability on a basic physics system, their transfer performances on an advanced physics system, and their physics misconceptions. I also identified which application of visuo-haptic simulation was the most effective.

Chapter V provides a summary of the results and relates the empirical findings to the grounded learning experience framework. The limitations of the studies, the theoretical contributions, and the practical implications are also discussed. Chapter V concludes this dissertation with possible directions for future research.

Chapter II

LITERATURE REVIEW

This chapter provides a review of literature relevant to this dissertation. This review begins with descriptions of mental models of systems, mental model construction, and constraints in mental model construction in order to provide the foundation to theories of learning using mental models. Discussion on cognitive load theory, compensations for working memory capacity limits, grounded cognition, and multimodal representation are then examined in order to consider visuo-haptic representation as a means to help people process information during instruction. The use of visuo-haptic representation in a priming condition is then examined and considered as a means to activate people's relevant prior experiences. The importance of physics and the practice of conceptual physics are discussed to provide reasons for choosing physics systems as the content subject for this dissertation. In addition, the design of a catapult simulation that accommodates different types of visuo-haptic representation is presented. This chapter concludes by proposing the grounded learning experience framework.

Mental Models

How did Newton deduce the law of universal gravitation from a fallen apple? As the story goes, Newton was already interested in knowing how the universe works. Inspired by his observation of a fallen apple, Newton compared the force needed for an apple to fall with his calculation of the force needed for the moon to stay in Earth's orbit. After factoring in the difference in mass and distance, Newton concluded that both forces are based on the same constant, which he later named "gravitational constant." Using this constant, Newton established the law of universal gravitation and used it to explain why objects fall toward earth and predict how planets move in space.

Of course, not everyone can make a great scientific discovery out of an ordinary observation, but this process is shared by many. For example, basketball fans often try to predict who will win the NCAA Championship by observing each college basketball team's performance during the regular season. How do people learn from the information they received? For decades, researchers on human cognition have been trying to answer this question by understanding the cognitive processes behind how people learn about their surroundings and predict behaviors. (Barnett et al, 2000; Craik, 1943; de Kleer & Brown, 1983; Gentner & Stevens, 1983; Johnson-Laird, 1983; Kaiser, Proffitt, & McCloskey, 1986; Mayer, 2001; McCloskey, 1983; Redish, 1993; Seel & Strittmatter, 1989). From their work, the theory of mental models has emerged to explain an individual's thought process.

The term "mental model" was first used by Craik (1943) in his book, *The Nature of Explanation*, to describe how people use internalized models to represent their interaction with the external world. Since then, mental models have been used to provide an effectively way in dealing with systems that are difficult to comprehend and master (Barnett et al, 2000; Redish, 1993). In a mental model paradigm, people learn by actively constructing information into meaningful mental representations (Mayer, 2001). People can then use their mental representations as means to understand both real and imaginary situations and to explain these situations to others (Seel & Strittmatter, 1989). The following subsections focus on further defining mental models, understanding mental model construction, and discussing possible constraints in mental model construction.

Mental Models of Systems

Since their inception, mental models have been separately developed along two perspectives: mental models of logical reasoning and mental models of systems. In mental models of logical reasoning, Johnson-Laird (1983) postulated that people solve logical reasoning tasks by creating a model of premises. Premises are conditions within logical reasoning tasks. These premises are formed from people's perception, imagination, or comprehension of factual information. People infer a conclusion of a logical reasoning task by reflecting on the underlying relationship between premises and finding a description that satisfies all premises in a model. In other words, a conclusion is valid if it satisfies all premises within a model. If a counter-example is found, the conclusion loses its validity

Using mental models to solve logical reasoning task is nevertheless subject to some significant constraints. An interesting principle in mental models for logical reasoning is that each mental model only represents one possibility (Johnson-Laird & Byrne, 2002). Some researchers have argued that this principle does not explain other aspects of human reasoning such as probabilities, which could produce a range of possible outcomes (Oaksford & Chater, 2007). In addition, the ability to conduct logical reasoning with mental models is affected by factors such as age and working memory (Barrouillet, et al., 2000). In short, mental models of logical reasoning have a rather limited generalizability.

A more generalizable perspective of mental models is mental models of systems. Systems are collections of interrelated concepts that, when considered together, perform certain functions. Mental models of systems are an interdisciplinary framework that include reasoning by analogy (Gentner & Stevens, 1983), comprehension of complex physical systems (de Kleer & Brown, 1983; Kaiser, Proffitt, & McCloskey, 1986; McCloskey, 1983), and the acquisition of technical knowledge (Norman, 1983). Gentner and Stevens (1983) first proposed the use of mental models to represent physical systems in the world and predict possible behaviors from such systems. From this perspective, mental models function as internal representations that are used to explain external systems. Although using mental models to represent external systems is generalizable to many tasks and domains, each mental model differs between task and domain.

Mental models of systems explain external systems through the causal relations between elements. Knowing how the elements causally relate to each other helps people adapt to changes in both mental models and the external systems that the models represent. This knowledge further helps people predict how external system operates in unexpected events. Tsuei, Hachey, & Black (2004) best defined mental models of systems by summarizing their five characteristics: (1) they consist of entities that are laid out spatially and interact with each other functionally; (2) they are dynamic; (3) they are imagistic; (4) they have a causality component in which entities are causally connected; and (5) they can be "run" in the mind.

Mental models of systems serve several practical functions in learning about systems, including: explanatory (Rickheit & Sichelschmidt, 1999), predictive (Williams, Hollan, & Albert, 1983), inferential (Schwartz & Black, 1996), and preparatory for future learning (Schwartz, Martin, & Pfaffman, 2005). In addition, Chan and Black (2006) proposed that the most powerful function of mental models of systems is equipping learners with the ability to construct manipulable imaginary worlds. Using this function of mental models, people can transfer their understandings of one system into other systems across different domains.

In this dissertation, I adopt mental models of systems' perspective because of its generalizability. For the purpose of this research, a mental model is defined as the conceptual representation of the information to be learned. Furthermore, I place a particular emphasis on how mental models are constructed to facilitate people's understanding of systems in this dissertation

Mental Model Construction

Mental models help individuals achieve structural insight, understand relations, promote conceptual change, and learn at deeper levels (Bryant & Tversky, 1999; Chi, 2000, 2005; de Kleer & Brown, 1983; DiSessa, 1993; Gentner & Stevens, 1983; Mayer, 2001; Kuhn, Black, Keselman, & Kaplan, 2000; Vosniadou & Brewer, 1992). In order to apply mental models to the learning of new systems, it is important to understand how mental models are constructed. There are two perspectives on mental model construction: model formation (de Kleer & Brown, 1983) or interaction with external system (Norman, 1983).

According to de Kleer and Brown (1983), a mental model has two primary components: entities or individual concepts in the domain and general causal knowledge. During the construction of a mental model, entities within the domain are connected together through their causal relations and gradually form a chain of events. This process is called model formation. When this process is completed, a web of causal relations has simultaneously connected all entities within a boundary condition set by the entities' domain and formed a governing relation that simulates system behaviors.

Kirchoff's voltage law (KVL) in an electrical circuit is a good example to demonstrate model formation. In KVL, active devices (electrical circuit components that generate energy, e.g. battery) and passive devices (electrical circuit components that consume energy, e.g. resistor) are entities. The boundary condition dictates that the total energy equals zero within a closed loop of circuit. When a closed loop of circuit only has either an active device or a passive device, energy is neither produced nor consumed. When a closed loop of circuit includes one active device and one passive device, the energy consumed by the passive device equals the energy produced by the active device. When a closed loop of circuit has one active device and two or more passive devices, the sum of energy consumed by each passive device equals the energy produced by the active device. When a closed loop of circuit includes two or more active devices and one passive device, the energy consumed by the passive device equals the sum of energy produced by each of the active devices. By forming the web of causal relations between passive and active devices within the boundary conditions, people construct a mental model for KVL.

Alternatively, Norman (1983) envisioned mental models as naturally evolving mental representations that people construct through their interaction with external systems. From this perspective, people constantly compare their relevant prior experiences to external systems. Based upon this comparison, people continue to modify their mental models until the models are workable for learning the external systems. Since mental models in this process are constructed on existing experiences, such a process helps people to expedite mental model construction. Without relevant prior experiences, people can take a long time in building workable mental models.

I maintain in this dissertation that both perspectives on mental model construction are valid. In addition, I argue that the main difference between these two perspectives is the activation of relevant prior experiences. When people have an activated relevant prior experience, it can be used to interact with the external system and expedite the modification process. When people do not have an activated relevant prior experience, instruction needs to be carefully designed to promote simultaneous processing of entities, casual relations, and boundary conditions.

Constraints on Mental Model Construction

Formal education has achieved some success in promoting students' concept understanding but often failed to promote system understanding (e.g., students know the definition of force, mass, and acceleration but are often unsure about the causal relations between these three concepts). As a result, students often view systems as collections of concepts without knowing how these concepts function with on another (Hmelo, Marather, & Liu, 2007, Honey et al., 1991). Additionally, students are often asked to develop accurate mental models for scientific systems that have invisible factors, complex abstractions, and no real-life referents (Chi, Feltovich, & Glaser, 1991). For example, in studies on the learning of electric fields, a complex physical system with many invisible factors in an abstract three-dimensional space and without obvious real-life referents, it is revealed that students have trouble understanding how charges move through electric fields. Students encounter this difficulty because they cannot visualize how force distribution in a vector field translates into the motion of the charge (Chambers & Andre, 1995; Dede, Salzman, Loftin, & Sprague, 1999; Furio & Guisasola, 1998).

However, this difficulty can be resolved if students' relevant prior experiences were activated. For example, if students can visualize a videogame character as a charge and a vector field as the sequence of directional keys that they need to press on a keyboard in order to move the character in different directions, they might be able to better understand electric fields. In other words, people's ability to construct accurate and comprehensible mental models is constrained by their ability to activate relevant prior experiences. To resolve this constraint, priming is considered, and the literature on its effect is reviewed in a later section.

Without the activation of relevant prior experiences, people need to construct mental models through model formation. However, simultaneously processing complex casual relations in a mental model poses a heavy demand on people's working memory. As a result, people's ability to construct a complete mental model is constrained by their working memory capacity limits. To resolve this constraint, working memory and ways to compensate for working memory capacity limits are considered below.

Working Memory

Working memory is a limited capacity system that allows one to store task-relevant information in a highly active state so that it can be easily accessed, evaluated, and transformed into cognitive activities (Ang & Lee, 2008; Smith & Kosslyn, 2006). According to Baddeley and Hitch's (1974) multicomponent model of working memory, working memory has a central executive component that supervises information, directs attention to relevant information, and coordinates cognitive processes for the slave systems. Under the central executive are three slave systems: phonological loop, visuospatial sketchpad, and episodic buffer.

Phonological loop includes the phonological store and the articulatory. The phonological store collects phonological information and the articulatory maintains phonological information through rehearsal. Visuospatial sketchpad is divided into a visual subsystem and a spatial subsystem (Baddeley & Lieberman, 1980). The visual subsystem deals with visual information such as shape, color, and texture (Logie, 1986). The spatial subsystem focuses on spatial skills that deal with location and numerical reasoning (Gunderson et al., 2012). Together, visuospatial sketchpad stores visual and spatial information for constructing and manipulating visual images, mental representations, and spatial relations. Episodic buffer links phonological and visuospatial information as well as information obtained from other possible modalities and integrates them into a unitary episodic representation (Baddeley, 2000).

Alternatively, Cowan (1995) proposed that representations in working memory are a part of short-term memory that is a subset of the representation in long-term memory. In this working memory model, long-term memory representations are prompted by sensory stimuli and turn into an activated short-term memory. Within this activated short-term memory, a focus of attention is formed to direct attention outward to stimuli or inward to long-term memory and control voluntary processing in the central executive of working memory. In other words, working memory is the activated state of short-term memory that can be used to comprehend sensory stimuli through representations in long-term memory and process sensory stimuli into representations in long-term memory.

Working memory is crucial in people's abilities to process complex tasks, such as understanding and reasoning about a system. However, processing these complex tasks can place a heavy burden on working memory and lead to counterintuitive results such as less learning or forming misconceptions (Feltovich, Coulson, & Spiro, 2001; Hmelo-Silver & Azevedo, 2006; Narayanan & Hegarty, 1998). This section focuses on working memory capacity limits and possible ways to compensate for these limits.

Working Memory Capacity Limits and Cognitive Load Theory

Earlier work on working memory capacity limits focuses on the phonological loop. Miller (1956) suggested that the memory span of young adults is 7±2 "chunks" of elements. Later research by Cowan (2001, 2005) further identified that working memory has a capacity limit of four chunks in young adults and fewer in children or older adults. Much of the research on phonological working memory capacity limits has shed light on how the capacity of transferring information to and from long-term memory can be improved in order to expand the span of chunks remembered (Ericsson & Kintsch, 1995; Gobet, 2000).

Opposite to phonological working memory that focuses primarily on memorizing textual information, visuospatial working memory focuses on processing visual information and spatial relations. Since mental models are images of the system (Norman, 1983) and entities in a mental model are laid out spatially (Tsuei, Hachey, & Black, 2004), a mental model can be considered as the visualization of a system. Therefore, the visuospatial sketchpad is treated with more attention in this dissertation because it directly addresses the information processing related to mental model construction.

Visuospatial sketchpad is the location where mental imagery is formed, manipulated, and transformed (Logie, 1995). Constructing a mental model by simultaneously processing the visualization of causal relations between entitles is a complex cognitive task. Furthermore, maintaining causal relations between entitles while manipulating these causal relations in a dynamic mental model is also a demanding cognitive task. Processing and maintaining task-relevant information often compete for the same resources in working memory (Just, Carpenter, & Hemphill, 1996). Therefore the processing capacity in visuospatial working memory can limit the construction of mental models. As a result, people may lose part of their visualization of a mental model when they try to manipulate it and vice versa.

This difficulty in simultaneously visualizing and manipulating mental models can be attributed to excessive demand on the cognitive load. Cognitive load is the density of attentional demands in the central executive component of working memory (Barrouillet, Bernardin, & Camos, 2004). In the cognitive load theory, Sweller and Chandler (1994) proposed that human beings have limited memory stores. During a complex cognitive task, simultaneously processing information creates cognitive overload to the executive control of working memory. In order to effectively process information, people need to reduce unnecessary cognitive loads.

There are three types of cognitive load: intrinsic, extraneous, and germane. The intrinsic cognitive load is the complexity of the content. Although the complexity of the content cannot be changed, the content can be broken down and into smaller sections and taught separately before rejoined together at a later time. The extraneous cognitive load is determined by how information is presented to learners, and it can be controlled by instruction designers. In a poorly designed instruction, one modality can be overloaded with processing demands. For example, Chandler and Sweller (1992) proposed that when the same modality is used to process various forms of information (e.g., processing both texts and images through visual channel), people's attentions split between forms of information, and this leads to less learning. This is called the split-attention effect. To overcome this overload, Mayer and Moreno (2003) proposed off-loading these processing demands to another modality. By off-loading, people can better process information into long-term memory within their limited working memory capacity and overcome the information processing constraint in mental model construction.

The germane cognitive load is used to process and construct information into schemas. Schemas are organized patterns of thought or behavior stored in long-term memory (Bartlett, 1932). Schemas can be also considered as organized sets of knowledge, and they are the key units in evaluating an instructional design (Paas, Renkl, & Sweller, 2004). Schema acquisition, which is the process of organizing information into schemas and using them to deal with new information, is an important process in learning and skill development. Schema acquisition can be explained through the focus of attention in Cowan's (1995) working memory model, where information (i.e., sensory stimuli) is processed into representations in long-term memory. Therefore, promoting the germane cognitive load expedites schema acquisition and helps people quickly learn new knowledge. The concepts of schema and schema acquisition are very similar to mental model and mental model construction. In fact, Jagacinski and Miller (1978) define mental models as special cases of schemas. Whereas schemas are mental representations of generic concepts stored in memory, mental models are more task specific (Stein & Trabasso, 1982). Based on schemas' relevance to mental models, I maintain in this dissertation that schemas acquisition contributes to mental model construction. Additionally, since people's schema includes their prior experiences (Sedikides & Green, 2000), activating prior experiences can help schema acquisition. In short, activating relevant prior experiences promotes the germane cognitive load and leads to mental model construction, and this process will be discussed in a later section on priming.

In order to promote mental model construction within a limited working memory capacity, people need a learning experience where the intrinsic cognitive load is at a moderate level, the extraneous cognitive load is reduced to the minimum level, and the germane cognitive load is promoted to the maximum level. Since the extraneous cognitive load can be controlled by instruction designers, several theories have emerged to specifically address the extraneous cognitive load.

Compensating Working Memory Capacity Limits

Several theories that address compensations for working memory capacity limits have shed light on ways to reduce the extraneous cognitive load, namely dual-coding theory (Paivio, 1986; Paivio, 1991), cognitive theory of multimedia learning (Mayer, 2001; Mayer & Moreno, 2003), and common coding theory (Prinz, 1997; Prinz, 2005). According to Paivio, people learn through two methods: verbal associations and visual imagery (Paivio, 1971). In Paivio's dual-coding theory, verbal and visual information are processed differently in two independent yet complementary cognitive subsystems (1986). Therefore, information that can be presented in both analogue codes (i.e., images) and symbolic codes (i.e., words) benefits memory retrieval and comprehension. Dual-coding theory's emphasis on the importance of visual and verbal information has inspired further research using multimedia in learning, such as Mayer's (1997, 2001) cognitive theory of multimedia.

Built on Baddeley's (1974) multicomponent model of working memory and Paivio's (1986) dual-coding theory, cognitive theory of multimedia suggests that learners actively select, organize, and integrate information from separate verbal and visual sources (Mayer, 1997). At the core of cognitive theory of multimedia is the modality principle which states that if the materials contain both verbal and graphical information, the verbal information should be given in auditory format (Mayer 2001). This is because separate components of working memory process auditory (i.e., phonological store) and visual (i.e., visuo subsystem) information. Consequently, carefully designed multimodal instructional materials reduce the extraneous cognitive load by off-loading processing demands from the visual modality to the auditory modality (Mayer & Moreno, 2003).

However, there is not enough empirical evidence to determine if words and images are the only ways that people remember or comprehend information (Pylyshyn, 1973). As an alternative to dual-coding theory, the common coding theory describes a direct link between perceptual representation and motor representation (Prinz, 1997; Prinz, 2005). This theory claims that there is a shared representation for both perception and action: seeing an event activates the action associated with the event, and performing an action activates the associated event. In other words, there is a visuo-haptic representation that also promotes learning. This theory confirms the role episodic buffer plays in working memory (Baddeley, 2000) and is consistent with the off-loading method to reduce the extraneous cognitive load (Mayer and Moreno, 2003).

In summary, reducing the extraneous cognitive load in working memory is promising in promoting mental model construction. Based on research in ways to compensate for working memory capacity limits, I intend to test the efficacy of visuo-haptic representation in promoting mental model construction through reducing cognitive load in working memory. To this end, this following section considers the embodiment perspective to find more evidences that support visuo-haptic representation.

Embodiment Perspective and Multimodal Representation

In the past fifteen years cognitive scientists have been exploring the embodiment perspective (Anderson, 2003; Barsalou, 1999; Barsalou, 2008; Barsalou 2010, Glenberg, 2010; Robbins & Aydede, 2009). The embodiment perspective indicates that cognition arises from bodily interaction with the world (Thelen et al, 2001). Stemming from the embodiment perspective are two related considerations of embodiment: embodied cognition and grounded cognition. The following discussion provides more precise definitions for each consideration.

Embodied Cognition

Embodied cognition focuses on the relationship between imagery, action, and perception (Barsalou, 2008; Barsalou, 2010; Glenberg, 2010). In the embodied cognition paradigm, studies have mostly been conducted on the relations between either imagery and perception or action and perception. In their work on imagery and mental model reasoning, Schwartz and Black (1996) combined the knowledge of a gear system with the images associated with gear rotation.

They concluded that people's perceived imagery of the gear rotation becomes a referent to their mental models and directly inform their conceptual understanding of the gear system. Additionally, in Boroditsky and Ramscar's (2002) study of spatial priming and orientation of time, people's orientation of time are altered when they are primed to imagine an object as either coming towards them or moving away from them.

Alternatively, the relationship between action and perception has been the focus of many studies as well. Wells and Petty (1980) found that nodding while listening to persuasive messages leads to more positive attitudes toward the messages. Niedenthal (2007) found that placing a pen in a person's mouth to facilitate smiling helped the individual to have more positive emotions toward both positive and negative cues. Broaders, Cook, Mitchell and Goldin-Meadow (2007) found that gestures are effective in revealing children's implicit memory about a subject and allowing it to become more receptive to instruction. These studies have shown that embodying image and action affects people's perception of information and promotes their cognitive processes.

However, these studies of embodied cognition did not account for the effect of environmental cues, which are information from the environment that is associated with but not controlled by people's actions. For example, people can feel the weight of a rock when they pick it up, but the heaviness of this rock does not change by people moving it around. Perception changes in embodied cognition are rooted in people's own action and interpretation of visual information and not from environmental cues. Therefore, I operationally define embodied cognition in a limited manner as people deriving information from their active interaction with image and action. In reality, people also learn from passively receiving information from the environment.

Grounded Cognition

Grounded cognition proposes a more completed characterization of embodiment that combines the mind, the body, and the world (Barsalou, 2008; Barsalou, 2010). In addition to the construct of embodied cognition, grounded cognition emphasizes that information from the environment is also an important factor in embodiment. Grounded cognition suggests that conceptual learning is derived from the dynamic interactions between the body and the physical world (Barsalou, 2008; Barsalou, Niedenthal, Barbey, & Ruppert, 2003; Gibbs, 2005; Glenberg, 1997; Lakoff & Johnson, 1999; Smith & Gasser, 2005; Wilson, 2002). In this sense, grounded cognition provides a broader and higher level definition for the embodiment perspective and it is defined as people deriving information from their active interaction with image, action, and environmental cues.

According to the grounded cognition paradigm, perceptions of the environment are essential for comprehending abstract concepts and complex systems. For example, people learn from their perception of winter that snow forms under a condition that is both cold and humid. With this information, people internalize the causal relation between the physics concepts of temperature and humidity and the weather condition of snowing. In other words, people construct a mental model through their perceptions of the environment.

In this dissertation, I adopt the perspective of grounded cognition and aims to promote mental model construction by providing people with a learning experience that includes information from the environment. In order to provide such a learning experience, simulations and multimodal representation are discussed in the following subsection to provide insights on the modalities that can deliver this learning experience.

Simulation and Multimodal Representation

Barsalou (2008) proposed that simulation is the process of reenacting neural modalities for perception, action, and introspection associated with an object. When people experience an object, elements of the object are captured through different neural modalities and associated together in the brain. When this experience is required at a later time, the captured elements are reactivated to simulate the original neural activation in the brain. For example, an experience of the object “book” can be integrated from neural modalities for perception associate with a book (e.g., the smell of paper, the weight of a book, etc.), action associated with a book (e.g., flipping through pages, carrying in a book bag, etc.), and introspection associated with a book (e.g., heavy, boring, etc.). By having experienced a book with these neural modalities, people can reconstruct their experience of a book when they think of a book or when they are exposed to other similar stimuli.

Neural modalities for perception representations are the easiest to be identified and standardized in a simulation since action and introspection vary from person to person. An individual’s perception is formed through multimodal representation, which captures neural modalities of an object across the visual, auditory, and haptic channels (Barsalou, 2008). Multimodal representation simulates perception of an object or a concept through different sensory modalities. For example, the concept of “mass” can be integrated from the visual indication of a numerical value of mass on a scale and the haptic feeling of a downward force from holding something heavy. Although people may not know the actual definition of mass, they can still form the concept of mass by integrating different modalities into a multimodal representation.

Visuo-Haptic Representation

Among all of the channels in a multimodal representation, the haptic channel is used the least in either formal or multimedia learning. The haptic channel is utilized in capturing the haptic modality, which includes somatosensory information (e.g. pressure, temperature, pain, etc.) and gestures (e.g. muscle movement and body position). This captured haptic modality is crucial in forming haptic perception, which is the process that helps people to learn about new objects. Studies on haptic perception have shown that people can rapidly and accurately identify objects by touch (Klatzky, Lederman, & Metzger, 1985; Lederman & Klatzky, 1987). Haptic perception is also primitive. Four month old infants can acknowledge the boundaries of two interconnected rings from interacting with the rings with only their hands (Robles-De-La-Torre, 2006). Other studies on haptic memory have also shown that infants as young as two months demonstrated the ability to recognize familiar object through touch (Catherwood, 1993; Lhote & Streti, 1998; Streri & Feron, 2008). Since infants' visual acuity do not reach adult standard of 20/20 until six months (Sokol, 1978), haptic perception is the first method that human beings learn first to explore the world.

In addition, studies on incorporating the haptic modality in training show that visuo-haptic representation is superior to visual representation or haptic representation alone in sensorimotor skill training (Morris, et al., 2007), perceptual motor skills training (Feygin, Keehner, & Tendick, 2002), and Matching Familiar Figure Test (Butter, 1979). Visuo-haptic representation has also shown to be effective in instruction. In the process of embodied understanding, students who interacted with the simulation using a joystick with two-dimensional (2D) force feedback outperformed those who did not use 2D force feedback (Han & Black, 2011).

In summary, haptic is a primitive modality that is especially effective when combined with the visual modality to form a realistic experience for skill training. Consolidating findings on the efficacy of visuo-haptic representation with reviews on compensations for working memory capacity limits and mental model of systems, I believe that incorporating visuo-haptic representation in instruction has the potential to promote mental model construction. In addition, I further distinguish the haptic modality into somatosensory information and gestures. Due to technological constraints, a majority of previous studies on the haptic modality investigated only its gestures function (see Butter, 1979; Chan & Black, 2006; Feygin, Keehner, & Tendick, 2002; Morris, et al., 2007). Gestures, when combined with the visual modality, improve people's abilities to process visuospatial information in their central executive of working memory (Chan, 2008). However, the combination of gestures and the visual modality can be meaningless when people use it to process environmental cues. For example, when people use a mouse to move simulated objects that are marked with different weights, their gestures cannot help them to distinguish the difference between each object and information received from such a gestures becomes incongruent with environmental cues.

Alternatively, somatosensory information, when combined with both the visual modality and gestures, improves people's abilities to process environmental cues into their own understanding. Using the previous example, when people use a device that can help them to feel the weight differences between each simulated object, they can process this congruent information from environmental cues into their understanding of "weight". Based on this premise, I contest that somatosensory information and gestures combined contains more task-specific information than gestures alone. Therefore, I manipulate somatosensory information in visuo-haptic representation by considering two types of simulation: visuo-haptic simulation and visuo-gestural simulation. Visuo-haptic simulation includes the visual modality and both of somatosensory information and gestures. Alternatively, visuo-gestural simulation only includes the visual modality and gestures.

Priming effect

The discussion on visuo-haptic representation above has shown that it can be meaningfully and effectively applied in instruction. This application of visuo-haptic representation is made under the assumption that people do not have activated relevant prior experiences when learning a new system. Yet what happens when people have activated relevant prior experiences? How could visuo-haptic representation be used differently to enhance learning in that scenario?

It is implied in Norman's (1983) perspective on mental model construction that that when people have an activated relevant prior experience, it interacts with the external system to expedite the modification process. From the cognitive load, activating relevant prior experiences promotes the germane cognitive load in the learning process and leads to better understanding and skill development. Based on these findings, priming effect is examined below as a mechanism to activate relevant prior experiences.

Priming is an implicit memory effect that happens when people's exposure to a stimulus influences their response to a later stimulus. This effect can be explained through Cowan's (1995) working memory model: stimuli prompts representations in long-term memory into an activated short-term memory, which is then used to comprehend later stimuli. For example, despite their memory loss, amnesic patients are able to perform similarly to control participants in completing word stem completion task, which is a task that primes participants with a first few letters of a word (Warrington & Weiskrantz, 1970). This is because priming activates unconscious memory of a word even if the word has been consciously forgotten. In fact, priming effect has shown to be more salient and long lasting than recognition memory (Tulving, Schacter, & Stark, 1982).

Priming has traditionally been categorized into several types: positive and negative priming (Mayr & Buchner, 2007), perceptual and conceptual priming (Beiderman & Cooper, 1992), direct priming (Forster & Davis, 1984), sematic priming (Marslen-Wilson, Tyler, & Waksler, 1994), associative priming (Stanovich & West, 1983), and response and masked priming (Klotz & Wolff, 1995). Most of the priming studies use either textual (semantic priming, associative priming, conceptual priming, etc.) or imagery (conceptual priming, response priming) association as the priming mechanism. These studies have shown that priming works best when the stimulation and later action are in the same modality (Reales & Ballesteros, 1999).

However, studies in neuropsychology have also shown that cross-modal priming is possible for visuo-haptic pathways, especially for people with damaged Broca's area or Alzheimer's disease (Reales & Ballesteros, 1999; Zurif, 1995). In a study of facial recognition, Casey and Newell (2005) found that people demonstrates better haptic recognition of a face when they have short-term familiarization of the face through visual representation priming. Other studies on cross-modal priming using the visuo-haptic pathway have revealed that visuo-haptic priming leads to quicker detection time in visual tasks (Young, Tan, & Gray, 2003) and quicker response time in picture-fragment completion tasks (Reales & Ballesteros, 1999). In short, these studies show that visuo-haptic priming can promote memory activation

In addition, priming effect is comparable to instruction in learning. Bock and Griffin (2000) found that the persistence of structural priming, a tendency to recreate a recently uttered syntactic structure in different word, is a form of implicit learning. Chartrand and Bargh (1996) found that priming produced the same results as explicit instruction. In a study on amnesic patients' paired-associate learning that involved related word pairs (e.g., table and chair), amnesic patients' performance were significantly worse than the control group when standard explicit learning instructions were used. However, when incidental learning was used as a priming condition, amnesic patients' performances were as good as the control group (Shimamura & Squire, 1984). Under the cognitive theory of multimedia learning framework, priming effect in learning is consistent with "weeding," a method that reduce cognitive load (Mayer & Moreno, 2003). Weeding is accomplished by using an activated short-term memory to eliminate extraneous material and process useful material into long-term memory. In other words, these studies show that priming effect can be as good as instruction in learning, if not more prominent, because it both reduced the extraneous cognitive load and promoted the germane cognitive load by.

Nevertheless, several researchers have cast doubt on the effectiveness or even the existence of priming effect, since many of the priming effects could not be replicated in further studies (Bower, 2012; Kahneman, 2012; Young, 2012). Doyen and his colleagues (2012) asserted that many priming studies suffer from the experimenter effect. In previous studies, priming effects have been accomplished through an exposure to stimuli that is too brief to determine if participants were responding to the activation of implicit memory in their minds or to researchers' bias. In this dissertation, I consider this drawback and propose to prolong the stimulus to ensure that it activates participants' prior experience in implicit memory. In sum, visuo-haptic priming has the potential to activate people's relevant prior experiences for mental models construction. This is accomplished through promoting the germane cognitive load and reducing the extraneous cognitive load in working memory.

Conceptual Physics

Reviews of the literature on mental models, working memory, grounded cognition, multimodal representation, and priming effects above have shown the potential of using visuo-haptic representation to construct mental models of systems. However, which system is the most suitable to examine the efficacy of visuo-haptic representation in mental model construction? The following section provides reasons for choosing physics as the content subject for this dissertation.

A system in the realm of physics incorporates the interactions between several physics concepts (e.g., force, mass, acceleration, energy, etc.). Physics systems provide explanation to how nature behaves. For example, Newton's law of universal gravitation explains how objects move toward earth and Newton's second law of motion explain why larger objects make more impacts when it hit the ground. These physics systems represent phenomena that people experience on a daily basis. Therefore, people have varied levels of experience with most physics systems.

Physics is generally considered to be the most important subject among all science domains because it is fundamental to understanding complex chemistry and biology (Hetzner, 2002). Many schools have thus adopted a "Physics First" curriculum that introduces physics to young students early so that they can build a better foundation for future science learning (Squire, Barnett, Grant, & Higginbotham, 2004). In order to learn physics at a young age, science educators suggest that it ought to be taught conceptually rather than mathematically (Forbus, 1997; diSessa, 1998). In conceptual physics, students learn and understand physics concepts and systems through experiments, labs, demonstrations, and visualizations (Furio & Guisasola, 1998; Forbus, 1997; Hewitt, 2002).

Despite the importance of physics, however, students oftentimes have difficulties in conceptually comprehending physics systems through observation (Chi, Feltovich, & Flaser, 1981). Many researchers have suggested that this difficulty is due to the fact that concepts in physics systems are often invisible and abstract, and students therefore cannot process their understanding of physics concepts and visualize the underlying interaction between concepts during observation (Andre & Ding, 1991; Bagno & Eylon, 1997; White & Frederiksen, 1998). In other words, trying to have students observe invisible factors in physics systems creates a high extraneous cognitive load that results in a cognitive overload in working memory. This innate difficulty in learning physics makes physics the ideal content subject for visuo-haptic representation and simulation, because such a simulation can help people both "see" and "feel" these invisible factors. Therefore, I use physics systems as the content subject.

Instrument Design

In this dissertation, I incorporate physics systems as the content subject to test the efficacy of visuo-haptic representation in constructing mental models. The instrument used in this dissertation is a catapult system. A catapult is a mechanical device that throws a projectile without the aid of explosives. The following subsections describe the operation of a haptic device and a catapult simulation. Together, they provide a visuo-haptic representation of the catapult system.

Haptic Device: The Novint Falcon

Contrary to many previous haptic studies that focused on manipulating gestures, I employ a haptic device that can be programmed to provide all participants with gestures while manipulating somatosensory information. Prior to this dissertation, studies on the process of embodied understanding had utilized both somatosensory information and gestures in learning gear rotation and pulley system (Han & Black, 2011). However, the haptic representation in those studies was limited by a two-dimensional joystick. As a result, participants were not able to experience congruent gestures when learning the pulley system. To overcome this device limitation, the Novint Falcon (see Figure 1), a three-dimensional force feedback joystick, is used in this dissertation.

The Novint Falcon allows people to naturally maneuver the joystick in a three-dimensional space while feel specific force profiles associated with simulated objects and motions. It produces more than two pounds of force in any direction and has high position and force resolutions. The Novint Falcon provides a realistic and task-specific haptic representation through both somatosensory information and gestures. Somatosensory information is realized through the force feedback of the Novint Falcon, and gestures are embodied in its three-dimensional movements. In this dissertation, gestures are always present while somatosensory information is determined by whether force feedback is provided or not. Prior exploratory studies have confirmed that participants have clearly distinguishable experiences with the manipulation on somatosensory information (Huang, Vea, & Black, 2011a, 2011b; Huang, Black, & Vea, 2012a, 2012b).

Figure 1: The Novint Falcon, a three-dimensional force feedback joystick.

Catapult Simulation

The catapult simulation used in this research is inspired by the interactive simulations from the PhET lab in University of Colorado at Boulder. The catapult simulation designed for this dissertation has the visual representation for the operation of a catapult (i.e., shooting a projectile) and the underlying physics concepts (i.e., energy, force, mass, etc.). The catapult simulation includes instructions on how to interact with the elements in the simulation, but it does not include any instruction on physics concepts and systems.

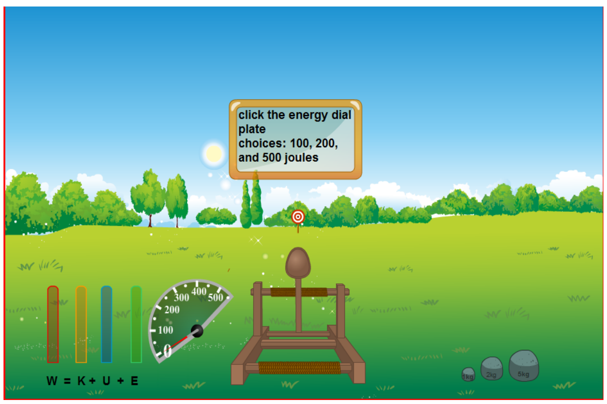

Figure 2: Screenshot of catapult simulation - viewed from behind.

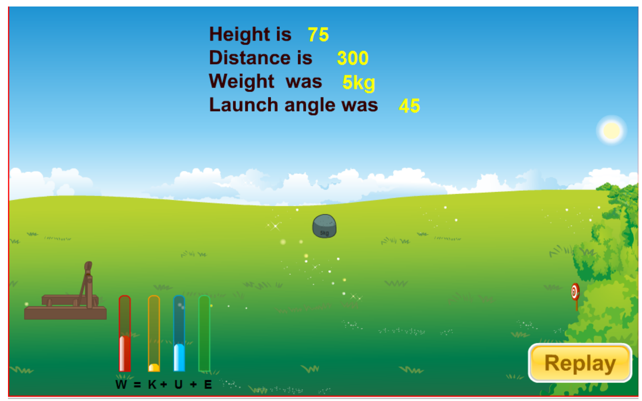

Figure 3: Screenshot of catapult simulation - viewed from the side.

Figures 2 and 3 illustrate two different perspectives of the catapult simulation. In the catapult simulation, users can set three different forces (100N, 200N, or 500N) for the catapult and choose three different mass (1kg, 2kg, or 5kg) for the projectiles. Information for the energy in the system is shown on the bottom left corner and information for the force and mass is shown on the top of the screen. When setting force or potential energy in the catapult and choosing different mass as the projectiles, users feel the specific force profile associated with their action or object. For example, when participants set the force by pulling down the catapult arm, they feel a force from the Novint Falcon that pulls against them.

When participants set the mass by moving the rock into the basket at the end of the catapult arm, they feel a downward force. When the projectile is released into the air, participants feel an upward force. As the projectile passes the peak of its trajectory and starts to fall to the ground, participants feel a downward force. Additionally, the difference in ratio between each force and mass is portrayed through the Novint Falcon. In the simulation, 2kg feels exactly twice as heavy as the 1kg.

This catapult simulation has been used in a couple of exploratory studies (Huang, Vea, & Black, 2011a, 2011b; Huang, Black, & Vea, 2012a, 2012b). These exploratory studies showed that the effectiveness of visuo-haptic representation on learning physics systems was not significantly varied by content difficulties or age. They also revealed that adult participants had a lower pretest performance than youth participants, indicating that adult participants have less prior knowledge in physics systems. This is a counterintuitive finding since adult participants were assumed to have more prior knowledge in physics systems than youth participants did. In this dissertation, I argue that adult participants had lower pretest performance because they initially relied on misconceptions in their prior knowledge. Therefore it is interesting to understand if visuo-haptic representation could remedy adult participants' physics misconceptions.

The Grounded Learning Experience Framework

Consolidating the insights from existing literature on mental models and visuo-haptic representation, I propose the grounded learning experience framework. There are two types of visuo-haptic representation in this framework: visuo-haptic simulation (VH) and visuo-gestural simulation (VG). When a visuo-haptic representation includes the visual modality, gestures, and somatosensory information, it is considered a visuo-haptic simulation. Alternatively, visuo-gestural simulation serves as a counterpart to visuo-haptic simulation and includes only the visual modality and gestures. These two types of visuo-haptic representation are differentiated by somatosensory information. Since somatosensory information allows people to experience and feel their environment, its presence constitutes a grounded experience. Therefore, a visuo-haptic simulation is also considered a grounded experience while a visuo-gestural simulation is not.

It is implied in Chan's (2008) model of cognitive processing in multimedia learning that a visuo-gestural simulation promotes mental model construction by affecting the central executive component in working memory. While the grounded learning experience framework concurs with this finding on visuo-gestural simulation, this framework postulates that visuo-haptic simulation also promotes mental model construction. This framework defines a mental model as the conceptual representation of the information to be learned. Therefore, people have a mental model for the system they are learning when they (1) demonstrate an improved understanding of the system and (2) are able to transfer their understanding into a similar and more advance system.

Furthermore, people construct their mental models through either model formation or their interactions with external systems. Which method is used depends on whether or not a relevant prior experience is activated. Therefore, the grounded learning experience framework accommodates both methods of mental model construction by proposing two types of application for visuo-haptic simulation: instruction or priming (see Figure 4). Instruction (I) starts with a visuo-haptic simulation. When this visuo-haptic simulation happens *while* participants are learning a physics system, it helps participants feel the invisible factors in the physics system. This process helps participants to off-load the information processing demands from the visual modality to the haptic modality so that they can independently process the perceived haptic and visual information within their limited working memory capacity. The effect of visuo-haptic simulation in instruction, or simply visuo-haptic instruction (VHI), is similar to the effect of dual-coding theory (Paivio, 1991) and cognitive theory of multimedia learning (Mayer & Moreno, 2003). Visuo-haptic instruction reduces participants' extraneous cognitive load in working memory and leads to a better mental model construction of the physics system for the learners. With this mental model, participants can transfer their understanding to other similar but more advanced physics systems.

Priming (P) also starts with a visuo-haptic simulation. When a visuo-haptic simulation happens *before* participants learn the content, participants' prior experiences are primed into an activated short-term memory by the visuo-haptic simulation to help participants relate to the content and process information into their long-term memory. As a result, visuo-haptic simulation in priming, or simply visuo-haptic priming (VHP), promotes their germane cognitive load in working memory. Additionally, an activated relevant prior experience allows participants to pay more attention to the essential information in the external system and eliminate other interesting but useless information, a process better described as "weeding" (Mayer & Moreno, 2003). This weeding process also reduces participants' extraneous cognitive load in working memory and promotes a better mental model construction. For example, when participants receive a visuo-haptic simulation with a sling shot, their prior experience about projectile motion is activated to become an existing conceptual representation about Newton's second law of motion. When they later experience a target physics system that also incorporates Newton's second law of motion, they can use their existing conceptual representation to interact with the external system and expedite mental model construction. With this mental model, participants transfer their understanding to other similar but more advanced physics systems.

In addition to reducing the extraneous cognitive load in working memory like visuo-haptic instruction, visuo-haptic priming also promotes the germane cognitive load. Therefore, visuo-haptic priming can expedite mental model construction, which then leads to better schema acquisition. Since schema acquisition is the key process in learning and skill development (Sweller & Chandler, 1994), this framework argues that visuo-haptic priming is more effective to mental model construction than visuo-haptic instruction.

Furthermore, since both visuo-haptic priming and visuo-haptic instruction reduce the extraneous cognitive load, participants' extraneous cognitive load is not further reduced when they experiences visuo-haptic instruction after visuo-haptic priming. Therefore, when learners received visuo-haptic instruction after they first received visuo-haptic priming, the effect of both visuo-haptic instruction and visuo haptic priming is less than the combination of individual effect of visuo-haptic priming and visuo-haptic instruction. In other words, there is a negative interaction between visuo-haptic priming and visuo-haptic instruction.

Additionally, since both visuo-haptic priming and visuo-haptic instruction promotes mental model construction, participants would have constructed mental models regardless of which types of application for visuo-haptic simulation they received. Therefore, the individual effect of visuo-haptic priming and visuo-haptic instruction on a later task is indistinguishable. Therefore, participants who received any type of visuo-haptic application should have the same level of understanding of a transfer task.

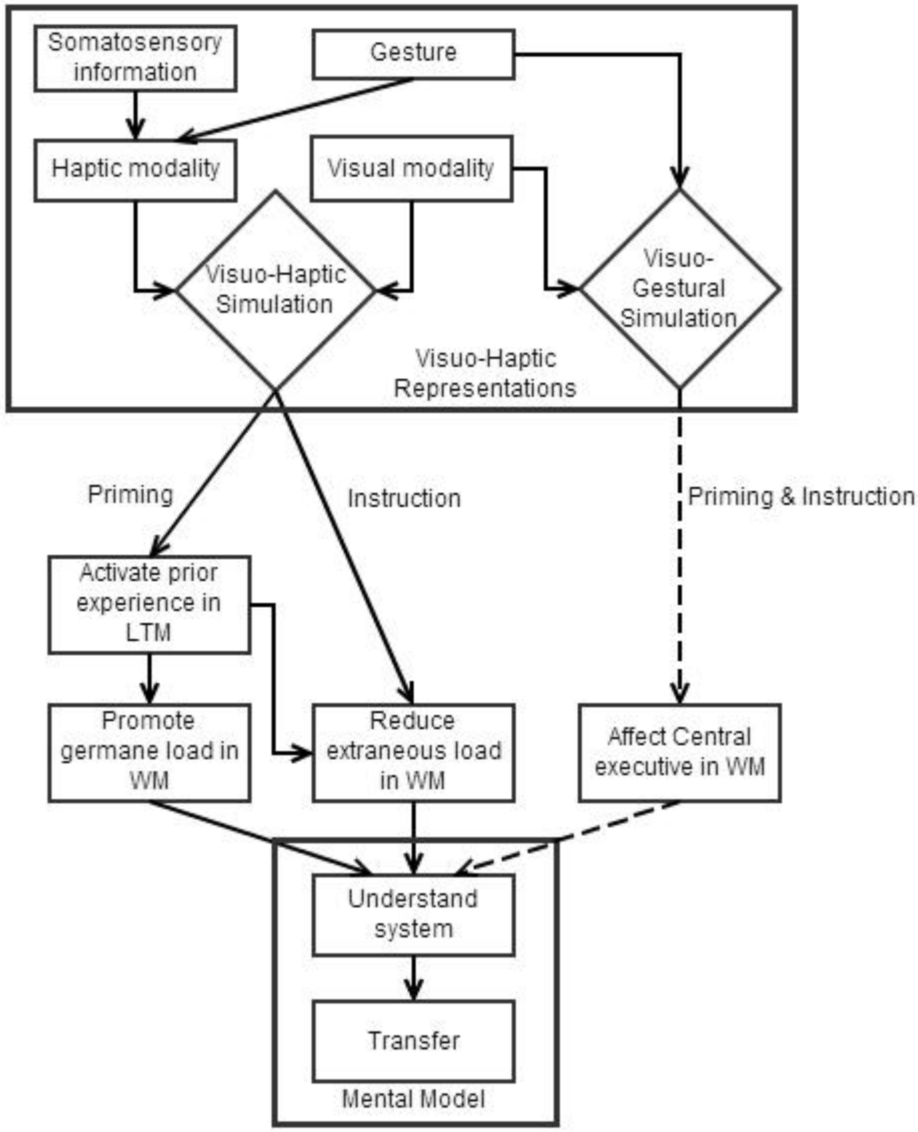

Figure 4: The grounded learning experience framework.

Chapter III

PILOT STUDY

This chapter describes a pilot study that investigated the instructional application of the grounded learning experience framework. The purpose of this pilot study was to examine how using different types of visuo-haptic representation in instruction affected people's mental model construction for physics systems. This chapter starts with two guiding research questions on the effects of visuo-haptic representations in instruction. Based on the literature review, two hypotheses were generated to address these research questions. This chapter then continues with a description of the participants and research design and provides more detail on the procedures of this pilot study. This chapter also includes a result section that presents outcomes from the data analyses. This chapter concludes with a discussion section that provides insights from participants' responses to exit interview questions and leads to the dissertation study discussion in Chapter IV.

Research Questions

The guiding research questions for this pilot study were:

(1) What effects did applying different types of visuo-haptic representation (visuo-haptic simulation or visuo-gestural simulation) during instruction have on supporting participants' understanding of a basic physics system?

(2) What effects did applying different types of visuo-haptic representation (visuo-haptic simulation or visuo-gestural simulation) during instruction have on

supporting participants' abilities to transfer their understanding from a basic physics system to an advanced physics system?

Hypotheses

H1: Based on the premise that both visuo-haptic simulation and visuo-gestural simulation lead to mental model construction in the grounded learning experience framework, I hypothesized participants who received visuo-haptic simulation and participants who received visuo-gestural simulation would both demonstrate a significant improvement in their level of understanding of the basic physics system.

H2: Contrary to visuo-gestural simulation that promotes mental model construction by affecting the central executive in working memory, visuo-haptic simulation leads directly to mental model construction by allowing participants to "off-load" information process demands to the haptic modality and reduces the extraneous cognitive load in working memory (Mayer & Moreno, 2003). Based on this premise, I hypothesized that participants who received visuo-haptic simulation during the instruction stage would have significantly higher gain scores for the basic physics system than those who received visuo-gestural simulation.

H3: Based on the premise in H2 which states that visuo-haptic simulation is superior to visuo-gestural simulation in mental model construction, I hypothesized that participants who received visuo-haptic simulation during the instruction stage would have significantly better transfer performances than those who received visuo-gestural simulation.

Participants

Participants were recruited from students enrolled in a technology course at a vocational community college. This community college is located in a suburban area near a major city in the northeastern region of the United States. In order to achieve a high degree of experimental control, participants' age and gender were carefully considered when assigning them to their groups. Twelve participants (six males and six females) with a mean age of 25.42 years ($SD = 4.852$) were assigned to the control group, and eleven participants (six males and five females) with a mean age of 25.360 years ($SD = 5.297$) were assigned to the experimental group. There was no significant difference in the mean age of the groups ($t = 0.250$, $df = 21$, $p = 0.980$).

Research Design

This study used types of visuo-haptic representation as the sole independent variable. Participants in the experimental group received visuo-haptic simulation (VHI), which included the visual modality, gestures, and somatosensory information. Participants in the control group received visuo-gestural simulation (VGI), which included only the visual modality and gestures.

This study was designed to include a tutorial stage, an instruction stage, and a transfer stage. The goal for the tutorial stage was to familiarize participants with the Novint Falcon, a three-dimensional force feedback joystick. During the tutorial stage, all participants received visuo-haptic simulation. The goal for the instruction stage was to have participants learn a basic physics system. During the instruction stage, the experimental group received visuo-haptic simulation and the control group received visuo-gestural simulation. The goal for the transfer stage was to have participants learn an advanced physics system. During the transfer stage, all participants interacted with a simulation using a mouse.

Three measurements were used to assess participants' performance in the instruction stage and the transfer stage. A pretest and a posttest were used to measure participants' level of understanding of the basic physics system that was used in the instruction stage. The pretest and the posttest (Appendix A), adopted from *Conceptual Physics* (Hewitt, 2010) and *Force Concept Inventory* (Hestenes, Wells, & Swackhamer, 1992; Hestenes & Halloun, 1995), involved the same ten multiple-choice problems related to the basic physics system. A transfer test was used to measure participants' level of understanding of the advanced physics system that was used in the transfer activity. The transfer test (Appendix B) involved a ten multiple-choice problem set adopted from *Conceptual Physics* (Hewitt, 2010).

Content and Material

Two physics systems were used in this pilot study: Newton's second law of motion and Newton's law of universal gravitation. These two systems mainly involve three entities: force, mass, and acceleration. Newton's second law of motion describes the relations between these three entities in $F = m \times a$. Based on Newton's second law of motion, Newton's law of universal gravitation introduces another mass variable and factors acceleration in terms of a gravitational constant over the square of distance between two masses into the equation. As a result, the formula for Newton's law of universal gravitation becomes $F = g\frac{m1 \times m1}{d^2}$. Based on the complexity of the formula, this study classified Newton's second law of motion as a basic physics system and Newton's law of universal gravitation as an advanced physics system.

The material used for the tutorial stage was the interactive tutorial package developed by Novint Technology, the company that designed and manufactured the Novint Falcon. Using the tutorial package, participants learned about the Novint Falcon's control and experienced force profiles in different scenarios. These scenarios involved: feeling textile differences, swinging a heavy object attached at the end of a string, catching a baseball, and shooting a pellet with a sling shot.

Two materials were used for the instruction stage: a YouTube video and a catapult simulation. This video, named *Professor Mac Explains Newton's Second Law of Motion* (Learnwithmac, 2011), introduced Newton's second law of motion to participants. This video prepared participants with the same amount of information in order to avoid any difference in their prior knowledge. The catapult simulation (see Chapter 2 for more detail) was an interactive catapult animation that works with the Novint Falcon. All participants used the Novint Falcon to set the catapult arm in position and move its projectiles. However, participants in the experimental group received visuo-haptic simulation and participants in the control group received visuo-gestural simulation.

Two materials were used for the transfer stage: a YouTube video and an interactive simulation on gravity. This video, named *Newton's Law of Universal Gravitation* (wwwphysics4me, 2009), introduced Newton's law of universal gravitation to participants. *Gravity Force Lab,* the interactive simulation used in the transfer stage, was developed by the PhET lab in University of Colorado at Boulder. In this simulation, participants saw two objects in the screen and used a mouse to change the mass for each of these two objects, the distance between these two objects, and the overall gravitational constant. As these variables changed, the changes in force between these two objects were displayed on top of the screen.

Procedures

During the learning activity, participants were first informed about the study. Participants who agreed to be a part of this study and signed the consent form then entered the tutorial stage. In the tutorial stage, participants explored different scenarios in the tutorial package and experienced visuo-haptic simulation from the Novint Falcon. Participants learned how to use the Novint Falcon through their own exploration without receiving any instruction. After twenty minutes of exploration, participants completed the tutorial stage and entered the instruction stage.

During the instruction stage, participants first spent fifteen minutes watching a video called *Professor Mac Explains Newton's Second Law of Motion*. After participants watched the video, they spent five minutes working on the pretest. After participants completed the pretest, they spent twenty minutes exploring the catapult simulation using the Novint Falcon before they spent another five minutes on the posttest. The instruction stage was concluded at the end of the posttest, and participants took a ten minute break before starting the transfer stage.

During the transfer stage, participants first spent six minutes watching a video called *Newton's Law of Universal Gravitation*. After participants watched the video, they explored an interactive simulation called *Gravity Force Lab*. After twenty minutes of exploration, participants spent a further five minutes to complete the transfer test. The transfer stage was concluded at the end of the transfer test. After the transfer stage, participants were individually interviewed about their learning experience before they were debriefed.

The total duration for this pilot study was 120 minutes with a ten minutes break after the first seventy minutes. This pilot study was completed in one regular class session. It is worth noting that the duration for a regular class session at the testing site was four hours, so the participants were physically and mental prepared for a long session.

Results

Pretest scores, posttest scores, gain scores (i.e. posttest – pretest), and transfer scores were calculated in percentages for purpose of the data analysis. For the basic physics system, there was no significant difference ($t = 1.220$, $df = 21$, $p = 0.236$) in mean pretest scores between the control group ($M = 32.500$, $SD = 8.660$) and the experimental group ($M = 37.273$, $SD = 10.091$). This result suggested that both groups had similar levels of prior knowledge about the basic physics system. There was a significant difference ($t = 15.326$, $df = 11$, $p < 0.001$) between the control group's mean posttest scores ($M = 60.000$, $SD = 9.535$) and mean pretest scores ($M = 32.500$, $SD = 8.660$). There was also a significant difference ($t = 10.768$, $df = 10$, $p < 0.001$) between the experimental group's mean posttest scores ($M = 73.636$, $SD = 11.201$) and mean pretest scores ($M = 37.273$, $SD = 10.091$). These results confirmed that both groups experienced a significant amount of improvement on their level of understanding for the basic physics system after the instruction (see H1 in this chapter).

For the basic physics system, there was a significant difference ($t = 2.465$, $df = 21$, $p = 0.022$) in mean gain scores between the control group ($M = 28.333$, $SD = 5.774$) and the experimental group ($M = 37.273$, $SD = 11.037$). This result confirmed that participants who received visuo-haptic simulation during the instruction of the basic physics concept had significantly higher gain scores than those who received visuo-gestural simulation (see H2 in this chapter). For the advanced physics system, there was also a significant difference ($t = 2.613$, $df = 21$, $p = 0.016$) in mean transfer test scores between the control group ($M = 45.833$, SD = 9.962) and the experimental group (M = 57.273, SD = 11.037) This results confirmed that participants who received visuo-haptic simulation during the instruction had a significantly better transfer performance than those who received visuo-gestural simulation (see H3 in this Chapter).

Summary

Several important findings were revealed in this pilot study. First, both visuo-haptic simulation and visuo-gestural simulation significantly improved the participant's level of understanding for the basic physics system. Secondly, visuo-haptic simulation helped participants gain a significantly higher level of understanding of the basic physics system than visuo-gestural simulation did. Finally, visuo-haptic simulation helped participants to achieve a significantly higher level of understanding of the advanced physics system than visuo-gestural simulation. These findings confirmed H1, H2, and H3 and suggested that visuo-haptic simulation was significantly better than visuo-gestural simulation in helping participants construct mental models for physics systems.

Additionally, results from participants' interview responses provided further insights into their learning experience in this pilot study. When answering the question "did this exercise help you learn physics and how", 64% of participants in the experimental group and 33 % of the participants in the control group believed that this exercise helped them learn physics. In particular, one participant in the experimental group described that this exercise helped him to "see and feel how things [like force, mass, and acceleration] were related so that the whole idea [of Newton's second law of motion] makes more sense." This response indicated that visuo-haptic simulation helped participants learn the physics system by allowing them to map environmental cues of different physics concepts in the physics system. Furthermore, this response suggested that using visuo-haptic simulation in learning the basic physics system promoted participants' abilities to off-load information process demand from the visual modality to the haptic modality and reduced the extraneous cognitive load in working memory. As a result, participants learned the basic physics system through achieving a better understanding of the causal relations between the entities studied during mental model construction.

When answering the question "were you doing anything differently to help you learn the second topic", 36% of the participants in the experimental group and 8% of the participants in the control group reported that they approach the advanced physics system with a better understanding of the relations between force and mass. This response confirmed that participants transferred their understanding for the basic physics systems into learning the advanced physics system. In addition, 27% of the participants in the experimental group demonstrated some forms of hand gestures in helping them understand the advanced physics system while none of the participants in the control group demonstrated any form of hand gestures. One participant in the experimental group demonstrated how he used his hands as the objects and changed the distance between two hands to help him "imagine a change of force in-between [their hands]." This result indicated that visuo-haptic instruction can prime participants to use hand gestures in learning about an advanced physics system.

Interestingly, when asked the question "which part of the exercise was most useful in helping you learn and why", 83% of all participants thought the tutorial stage was the most useful because it reminded them of similar activities they did before. This recalling of prior activities helped them by relating their relevant prior experience to the physics systems. 74%

of all participants made similar claims that they “kind of knew what this exercise was all about” after the tutorial stage. This result confirmed that participants’ relevant prior experience can be activated through the application of visuo-haptic simulation before instruction. This activation of prior experience was further investigated through the priming application of visuo-haptic simulation in the present dissertation study as reported in Chapter IV.

In summary, this present pilot study confirmed that visuo-haptic instruction is significantly more effective in mental model construction than visuo-gestural instruction. Results from this pilot study confirmed that visuo-haptic simulation promoted mental model construction through reducing participants’ extraneous cognitive load in working memory. In addition, it also provided a glimpse into the efficacy of visuo-haptic priming.

Chapter IV

DISSERTATION STUDY

This chapter describes a dissertation study based on the grounded learning experience framework. In this dissertation study, I examined how types of visuo-haptic representation and types of their application support participants' mental model construction for physics systems. According to the grounded learning experience framework, there are two types of visuo-haptic representation: visuo-haptic simulation and visuo-gestural simulation. Visuo-haptic simulation (VH) includes the visual modality, gestures, and somatosensory information. Visuo-gestures simulation (VG) only includes the visual modality and gestures. These two types of visuo-haptic representation are differentiated by somatosensory information, which is manipulated by providing force feedback to the haptic channel. There are also two types of applications for visuo-haptic representations: priming or instruction. When visuo-haptic representation takes place before content learning, it is considered to be a priming application. Alternatively, when visuo-haptic representation takes place during content learning, it is considered to be an instruction application.

This chapter begins with the guiding research questions for the present dissertation study. Hypotheses derived from the literature review are presented, followed by a description of the participants. The research design for this dissertation study, including the independent and dependent variables, the contents, and the study procedures, are described in detail, followed by the data analysis for each hypothesis and a secondary data analysis for the different question types. This chapter concludes with a discussion section.

Research Questions

The guiding questions for this dissertation study were:

(1) What effects did types of visuo-haptic representation (visuo-haptic simulation or visuo-gestural simulation) in different applications (priming or instruction) have on supporting participants' level of understanding for physics systems?

(2) Did types of visuo-haptic representation in priming affect participants' level of understanding from different types of visuo-haptic representation received in later instruction?

(3) Which type of application for visuo-haptic simulation (priming or instruction) made a more significant contribution to supporting the participants' level of understanding for physics systems?

(4) What effects did types of visuo-haptic representation (visuo-haptic simulation or visuo-gestural simulation) in different applications (priming or instruction) have on participants' level of physics misconceptions?

(5) Did types of visuo-haptic representation in priming affect participants' level of physics misconception from different types of visuo-haptic representation received in later instruction?

Hypotheses

H1: Based on the premise that visual-haptic simulation helps activate prior experience that promotes the germane cognitive load and reduces the extraneous cognitive load in working memory while visuo-gestural simulation only affects the central executive in working memory without activating relevant prior experiences, I hypothesized that participants who received visuo-haptic priming (VHP) would have significantly higher gain scores for the basic physics system, significantly better transfer scores for the advanced physics system, and significantly higher gain scores for the physics misconception tests than those who received visuo-gestural priming (VGP).

H2: Based on the premise that visuo-haptic simulation allows participants to "off-load" information process demands to the haptic modality and reduces the extraneous cognitive load in working memory while visuo-gestural simulation only affects the central executive in working memory, I hypothesized that participants who received visuo-haptic instruction (VHI) would have significantly higher gain scores for the basic physics system, significantly better transfer scores for the advanced physics system, and significantly higher gain scores for the physics misconception tests than those who received visuo-gestural instruction (VGI).

H3: Since visuo-haptic simulation reduces the extraneous cognitive load in both priming and instruction, I postulated that participants' extraneous cognitive load would not be further reduced when they experienced visuo-haptic instruction after receiving visuo-haptic priming. Therefore, the effect of receiving both visuo-haptic instruction and visuo haptic priming on learning the basic physics systems would be less than the combination of the individual effects of visuo-haptic priming and visuo-haptic instruction.

Additionally, since both visuo-haptic priming and visuo-haptic instruction promote mental model construction, I postulated that participants constructed a mental model of the basic physics system that can be transferred into their learning of the advanced physics system regardless of which types of application for visuo-haptic simulation they received. Therefore, the effects of types of application for visuo-haptic simulation on a later task would be indistinguishable and participants who received any type of visuo-haptic application should have the same level of understanding of a transfer task.

Based on these premises, I hypothesized that participants who received visuo-haptic simulation in both the priming and instruction stages (VHP-VHI) would not have significantly higher gain scores for the basic physics concept, transfer scores for the advanced physics concept, and gain scores between physics misconception tests than those who received visuo-haptic simulation in only priming stage (VHP-VGI) or instruction stage (VGP-VHI). In other words, there will be a negative interaction between types of visuo-haptic representation and the types of preceding application.

H4: Schema acquisition is the key process in learning and skills development (Sweller & Chandler, 1994). Since visuo-haptic priming promotes both the germane cognitive load and reduces the extraneous cognitive load, it was more likely this would expedite schema acquisition when compared to visuo-haptic instruction, which only reduces the extraneous cognitive load. Therefore, I hypothesized that visuo-haptic priming (VHP) would contribute more significantly to participants' gain scores for the basic physics system and their transfer performance for the advanced physics system than visuo-haptic instruction (VHI).

Participants

Participants in this study were 96 students (66 males, 30 females) recruited from students registered in introductory technology, mathematics, and sciences courses at a vocational community college. This community college is located at a suburban area of a major city in the northeastern region of the United States. The mean age for the participants was 24.4 (SD=4.852). The participants' population consisted of the following ethnicities: 38% Caucasian, 28% Hispanic, 18% Black, and 15% Asian. All participants held either a high school diploma or a GED. 81% of the participants had received their high school education in the United States and 19% of the participants had received their high school education in foreign countries that taught English in high school level. All participants had workable English communication skills. 84% of the participants had taken high school physics, and 94% of which received a grade C or below. All recruited participants signed the consent form and participated in this study during their regular class hour.

Research Design

In this dissertation study, I adopted a 2x2 between-subject factorial design (Table 1). Participants within each class session were randomly assigned to one of four experimental conditions. These conditions were the following:

(1) VGP-VGI: Participants in the VGP-VGI condition received visuo-gestural simulation in both the priming and instruction stages. Operationally, participants in this condition did not experience any force feedback.

(2) VGP-VHI: Participants in the VGP-VHI condition received visuo-gestural priming before they received visuo-haptic instruction. Operationally, participants in this condition only experienced force feedback in instruction.

(3) VHP-VGI: Participants in the VHP-VGI condition received visuo-haptic priming before they received visuo-gestural instruction. Operationally, participants in this condition only experienced force feedback in priming.

(4) VHP-VHI: Participants in the VHP-VHI condition received visuo-haptic simulation in both the priming and instruction stages. Operationally, participants in this condition experienced force feedback in both the priming and instruction stages.

Table 1: Representation of the 2x2 between subject factorial design

	Types of Visuo-Haptic Representation in Priming	
Types of Visuo-Haptic Representation in Instruction	**VGP-**VGI (1)	**VHP-**VGI (3)
	VGP-VHI (2)	**VHP-**VHI (4)

Independent Variables

In this dissertation study, I examined the grounded learning experience framework by manipulating the types of visuo-haptic representation used in the priming and in instruction stages. There were two independent variables in this study: types of visuo-haptic representation in priming stage (IV1) and types of visuo-haptic representation in instruction stage (IV2). Each independent variable included two conditions: visuo-haptic simulation (VH) and visuo-gestural simulation (VG). The only difference between these two conditions was the presence of somatosensory information, which was manipulated by the presence of force feedback in the Novint Falcon. In the visuo-haptic simulation condition, participants used the Novint Falcon to move in a three-dimensional workspace while experiencing realistic and task-specific force feedback from different objects they interacted with in the simulation. In the visuo-gestural simulation condition, participants still used the Novint Falcon to move in a three-dimensional workspace, but they did not receive any type of force feedback.

Dependent Variables

There were three sets of dependent variables: change in level of understanding from the learning activity (DV1), the level of understanding from the transfer activity (DV2), and the change in the level of physics misconceptions (DV3). Participants' ability to construct a mental model was demonstrated through their performances in DV1 and DV2. If participants achieved a better gain in DV1 and showed a higher performance in DV2, they were considered to have a better ability in constructing mental models of physics systems. The materials used to determine DV1, DV2, and DV3 were:

DV1: Change in level of understanding of learning activity was used to determine the effect of visuo-haptic priming (VHP) and visuo-haptic instruction (VHI) on participants' level of understanding for a basic physics system. Participants' level of understanding was determined by their problem-solving ability, and was measured through a pretest, a posttest 1, and a posttest 2. A pretest was used to determine a participant's initial level of understanding for the basic physics system and this was measured before the priming stage. A posttest 1 was used to demonstrate the effect of visuo-haptic priming (VHP) and visuo-gestural priming (VGP) and was measured between the priming stage and the instruction stage. A posttest 2 was used to determine a participant's final level of understanding for the basic physics system and was measured after the instruction stage. The pretest, posttest 1, and posttest 2 (Appendix C to Appendix E) were adopted and modified from *Conceptual Physics* (Hewitt, 2010). They shared the same format and question types: ten multiple choice problems, including six problems concerning the conceptual understanding for the basic physics system and four problems on the numerical understanding of the basic physics system. Participants had five minutes to complete each test. A gain scores between posttest 2 and the pretest (posttest 2 – pretest) was used to represent change in level of understanding of learning activity.

DV2: Level of understanding of the transfer activity measured participants' ability to transfer their understanding from a basic physics system learning activity to an advanced physics system. A transfer test was deployed after the transfer task to determine participants' level of understanding of the advanced physics system, which was also determined by their ability in problem-solving. This transfer test (Appendix F) was adopted and modified from *Conceptual Physics* (Hewitt, 2010). The transfer test also comprised ten multiple choice problems, including six problems concerning the conceptual understanding of the advanced physics system and four problems concerning the numerical understanding of the advanced physics system. Participants had five minutes to complete the transfer test.

DV3: Change in level of physics misconceptions measured the difference between participants' misconceptions in Newtonian force concepts before and after a grounded learning experience. It was measured through two misconception tests. Misconception test 1 was deployed during session 1, which took place two weeks before session 2. Misconception test 2 was deployed after transfer activity in session 2. *Force Concept Inventory* (Hestenes, Wells, & Swackhamer, 1992; Hestenes & Halloun, 1995) was used for the misconception tests. Force Concept Inventory (FCI) is a standardized measure of people's misconception in Newtonian force concepts. It has 30 multiple choice problems and needs to be completed in fifty minutes. In FCI, 60% is the threshold scores for an entry-level of understanding and 80% is the threshold scores for a mastery-level of understanding for college level participants.

In addition to the measurements for the dependent variables, four interview questions (Appendix G) were posed to each participant at the exit interview. These questions were designed to gain additional insight on whether (1) the grounded learning experience was effective in helping them learn physics systems; (2) the grounded learning experience changed the way they learned physics systems; (3) whether visuo-haptic priming (VHP) or visuo-haptic instruction (VHI) was more effective; and (4) the participants learned the physics systems by constructing mental models. Participants were asked to elaborate on their experiences. Qualitative information from responses to these interview questions were used to provide insight on quantitative findings that emerged from all dependent variables.

Content and Material

The content for the learning activity employed Newton's second law of motion and the content for the transfer activity employed Newton's law of universal gravitation. These two physics systems share the same basic forms of equations that mainly involve three entities: force, mass, and acceleration. Newton's second law of motion provides a perspective on how objects move in free space, and demonstrates the basic relationships between these three entities using the formula $F = m \times a$. However, Newton's law of universal gravitation provides a high level perspective on how objects affect each other's movements in the universe, and it introduces another mass variable and factors the acceleration in terms of gravitational constant by the square of distance between the two masses. As a result, Newton's law of universal gravitation demonstrates the causal relationship that exists between all its entities in a formula $F = g\frac{m1 \times m1}{d^2}$. Based on the complexity of formula, I classified Newton's second law of motion as the basic physics system and Newton's law of universal gravitation as the advanced physics system.

The material used for the priming stage was a sling shot simulation from Novint's interactive tutorial software. The sling shot simulation did not contain any textual information or instruction. Participants pulled the Novint Falcon back while holding any button to set the amount of elastic displacement in the sling shot. As they released the button, the sling shot released the projectile. When participants pulled a short distance on the Novint Falcon, the sling shot showed a small elastic displacement and the projectile flew a short distance after it was released. When participants pulled a long distance on the Novint Falcon, the sling shot showed a large elastic displacement and the projectile flew a long distance after it was released. In the priming stage, participants in the visuo-haptic simulation condition (VHP) experienced the force required to pull the Novint Falcon. This force was directly proportional to the distance pulled. Participants in the visuo-gestural simulation condition (VGP) did not experience any force at all.

The material used for the instruction stage was a catapult simulation. The Novint Falcon was used to interact with this simulation and to demonstrate force profiles for the different actions and objects. Participants did not receive any content instruction. The only instruction that participants had was on how to set the catapult arm to different force levels, how to choose different forms of mass and how to move it to the basket at the end of catapult arm, and how to release the projectile. In this simulation, participants set three different levels of force (100N, 200N, or 500N) for the catapult and chose three different forms of mass for the projectiles (1kg, 2kg, or 5kg). The information for the force and mass were shown on top of the screen once these were chosen by participants. When setting the force and choosing the mass, participants in the visuo-gestural simulation condition (VGI) did not experience any force while participants in the visuo-haptic simulation condition (VHI) experienced realistic and task-specific force feedback associated with different actions or objects.

For example, when participants set the force by pulling down the catapult arm, they experienced a force from the Novint Falcon that was pulling against them. When participants set the mass by moving the rock into the basket at the end of the catapult arm, they experienced a downward force. When the projectile was released into the air, participants experienced both an upward and a forward force. As the project passed the peak of the trajectory and started to fall to the ground, participants experienced both a downward and a forward force. Additionally, the difference in ratio between each force and mass variable was portrayed through the Novint Falcon (i.e. 2kg feels twice as heavy as 1kg).

An animated computer simulation on gravity was used for the transfer task. The computer simulation, *Gravity Force Lab,* was developed by the PhET lab in University of Colorado at Boulder. In this simulation, participants saw two objects on screen and they used a mouse and a keyboard to manipulate the mass of the two objects, the distance between the two objects, and the overall gravitational constant. As these variables changed, the changes in force between these two objects were displayed on the top of the screen.

Procedures

This study included two sessions. Before session 1, each participant was randomly assigned to one of the four experimental conditions (VGP-VGI, VGP-VHI, VHP-VGI, and VHP-VHI). During session 1, participants were first informed that they would be participating in a scientific research experiment on learning physics systems with simulation, and that their participation was voluntary. They were also informed that there would be several tests in this experiment, and neither the test results nor their participation would affect their course grade. After all willing participants signed and submitted the consent form, they were asked to spend fifty minutes on misconception test 1. The total duration for session 1 was sixty minutes.

Session 2 was held two weeks after session 1. In session 2, participants first entered the learning activity. In the learning activity, participants first spent five minutes on the pretest. After they completed the pretest, participants entered the priming stage and spent 20 minutes interacting with the sling shot simulation. After the priming stage, participants spent five minutes on posttest 1 before they entered the instruction stage. In the visuo-haptic instruction stage, participants interacted with the catapult simulation for twenty minutes. After participants completed the visuo-haptic instruction stage, they spent another five minutes on posttest 2 before they entered the transfer activity.

During the transfer activity, participants first entered the transfer task and interacted with *Gravity Force Lab* (PhET, 2011) for 20 minutes. After they completed the transfer task, participants spent five minutes on the transfer test and then had a ten-minute break. After participants returned from the break, they spent fifty minutes on misconception test 2. After the test, each participant was interviewed and debriefed within ten minutes. The total duration for session 2 was 150 minutes. The complete procedure for this study is illustrated in Table 2.

Table 2: Procedure for dissertation study

<table>
<tr><td rowspan="2">Session 1 (60m)</td><td rowspan="2"></td><td>Introduction and consent</td><td colspan="4">All participants</td><td>10m</td></tr>
<tr><td>Misconception test 1</td><td colspan="4">All participants</td><td>50m</td></tr>
<tr><td colspan="8">2 Weeks Break</td></tr>
<tr><td rowspan="10">Session 2 (150m)</td><td rowspan="5">Learning Activity (55m)</td><td>Pretest</td><td colspan="4">All participants</td><td>5m</td></tr>
<tr><td>Priming Stage (Sling Shot simulation)</td><td colspan="2">VHP</td><td colspan="2">VGP</td><td>20m</td></tr>
<tr><td>Posttest 1</td><td colspan="4">All participants</td><td>5m</td></tr>
<tr><td>Instruction Stage (Newton’s Second Law of Motion)</td><td>VHI</td><td>VGI</td><td>VHI</td><td>VGI</td><td>20m</td></tr>
<tr><td>Posttest 2</td><td colspan="4">All participants</td><td>5m</td></tr>
<tr><td rowspan="2">Transfer Activity (25m)</td><td>Transfer task (Newton’s Law of Universal Gravitation)</td><td colspan="4">All participants</td><td>20m</td></tr>
<tr><td>Transfer test</td><td colspan="4">All participants</td><td>5m</td></tr>
<tr><td rowspan="3"></td><td colspan="5">Break</td><td>10m</td></tr>
<tr><td>Misconception test 2</td><td colspan="4">All participants</td><td>50m</td></tr>
<tr><td>Exit interview</td><td colspan="4">All participants</td><td>10m</td></tr>
</table>

Results

This section starts with descriptive statistical data that provides more insight on the participants. These data includes: participants' mean scores for the tests, prior knowledge, gain scores for the basic physics system (DV1), transfer scores for the advanced physics system (DV2), and gain scores between misconception tests (DV3). All scores in this section are reported in percentages. Following the descriptive statistical data is the hypotheses test results. Several statistical analyses were used to determine the validity of the hypotheses for this dissertation study.

Participants' Mean Scores for Tests

Participants mean scores for the pretest, posttest 1, posttest 2, and the transfer test are presented in Figure 5. Two interesting trends can be observed from this chart. First, the differences between posttest 1 and pretest were greater than the differences between posttest 2 and posttest 1 for all groups. Since the difference between posttest 1 and pretest was attributed to the priming stage and the difference between posttest 2 and posttest 1 was attributed to the instruction stage, this result suggests that priming was more effective in facilitating learning of the basic physics concept than instruction.

Secondly, transfer test scores were not visually different for VGP-VHI, VHP-VGI, and VHP-VHI conditions, but their scores were visually different for the transfer scores for the VGP-VGI group. This result suggests that there was not a difference in participants' transfer performance as long as visuo-haptic simulation was presented in any part of the learning process.

The participants mean scores for the misconception tests are presented in Figure 6.

Since the entry-level threshold for FCI is 60%, this chart indicates that even though participants' misconceptions in Newtonian concepts were improved, they were still below entry-level.

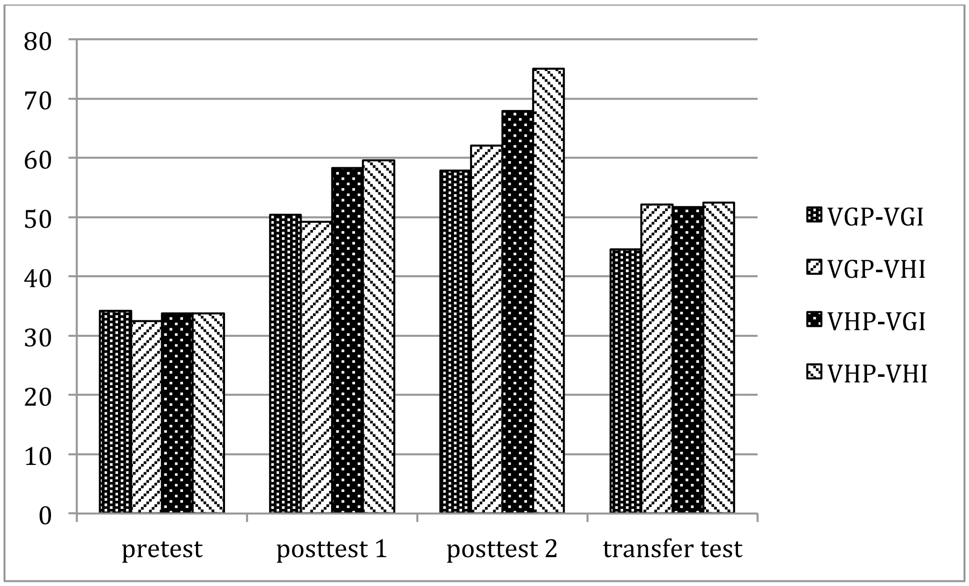

Figure 5: Participants' mean scores for the pretest, posttest 1, posttest 2, and the transfer test.

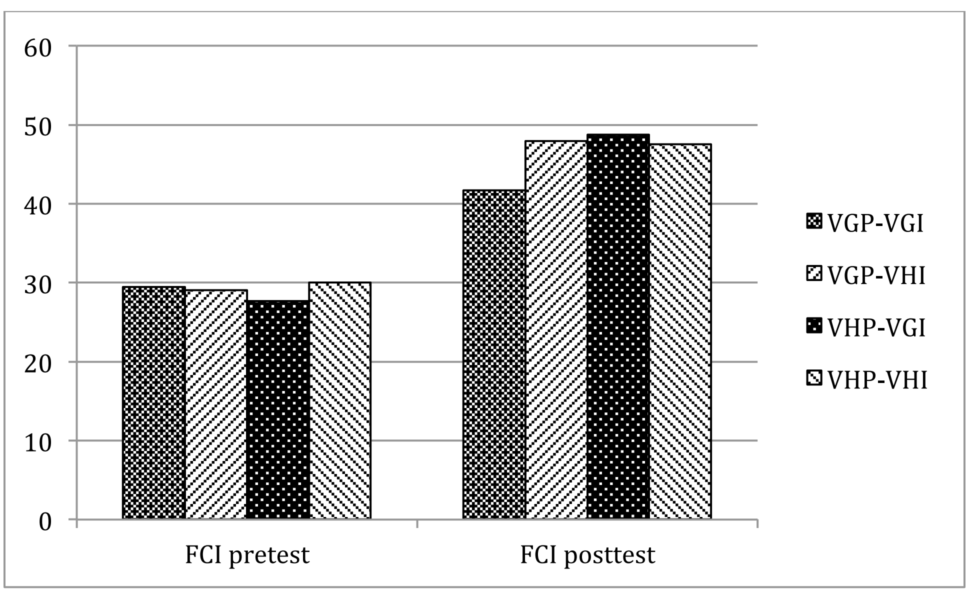

Figure 6: Participants mean scores for the misconception tests.

Prior Knowledge

Participants' prior knowledge was measured with both misconception test 1 and the pretest (Table 3 and Table 4). For misconception test 1, participants had a mean scores of 29.028 (SD = 6.838). There was no significant difference between each group, $F = 0.513$, $p = 0.674$, $\eta^2 = 0.02$. This result was below FCI entry-level threshold and indicated that participants had strong physics misconceptions. For the pretest, participants had a mean scores of 33.542 (SD = 10.759). There was no significant difference between the groups, $F (3, 92) = 0.105$, $p = 0.957$, $\eta^2 < 0.01$.

Table 3: Participants' prior knowledge – misconception test 1

		Types of priming		Total
		VGP	VHP	
Types of instruction	VGI	N = 24 M = 29.444 SD = 7.593	N = 24 M = 27.639 SD = 6.406	N = 48 M = 28.542 SD = 7.009
	VHI	N = 24 M = 29.028 SD = 6.098	N = 24 M = 30.000 SD = 7.36	N = 48 M = 29.514 SD = 6.702
Total		N = 48 M = 29.236 SD = 6.815	N = 48 M = 28.819 SD = 6.927	N = 96 M = 29.028 SD = 6.838

(Scores in percentage)

Table 4: Participants' prior knowledge – pretest

		Types of priming		Total
		VGP	VHP	
Types of instruction	VGI	N = 24 M = 34.167 SD = 9.743	N = 24 M = 33.750 SD = 11.349	N = 48 M = 33.958 SD = 10.466
	VHI	N = 24 M = 32.500 SD = 12.247	N = 24 M = 33.750 SD = 10.135	N = 48 M = 33.125 SD = 11.139
Total		N = 48 M = 33.333 SD = 10.980	N = 48 M = 33.750 SD = 10.644	N = 96 M = 33.542 SD = 10.759

(Scores in percentage)

Gain Scores for the Basic Physics System (DV1)

Participants' gain scores for the basic physics system represented the difference between their pretest scores and posttest 2 scores (i.e. posttest 2 – pretest). Participants' mean gain scores for the basic physics system are presented in Table 5 and the profile plot for the gain scores is presented in Figure 7. The result from the analysis of variance (ANOVA) is presented in Table 6.

Table 5: Participants' gain scores for the basic physics system – mean table

		Types of priming		Total
		VGP	VHP	
Types of instruction	VGI	N = 24 M = 23.750 SD = 8.242	N = 24 M = 34.167 SD = 10.589	N = 48 M = 28.953 SD = 10.766
	VHI	N = 24 M = 29.583 SD = 10.427	N = 24 M = 41.250 SD = 11.156	N = 48 M = 35.417 SD = 12.197
Total		N = 48 M = 26.667 SD = 9.749	N = 48 M = 37.708 SD = 11.343	N = 96 M = 32.188 SD = 11.895

(Scores in percentage)

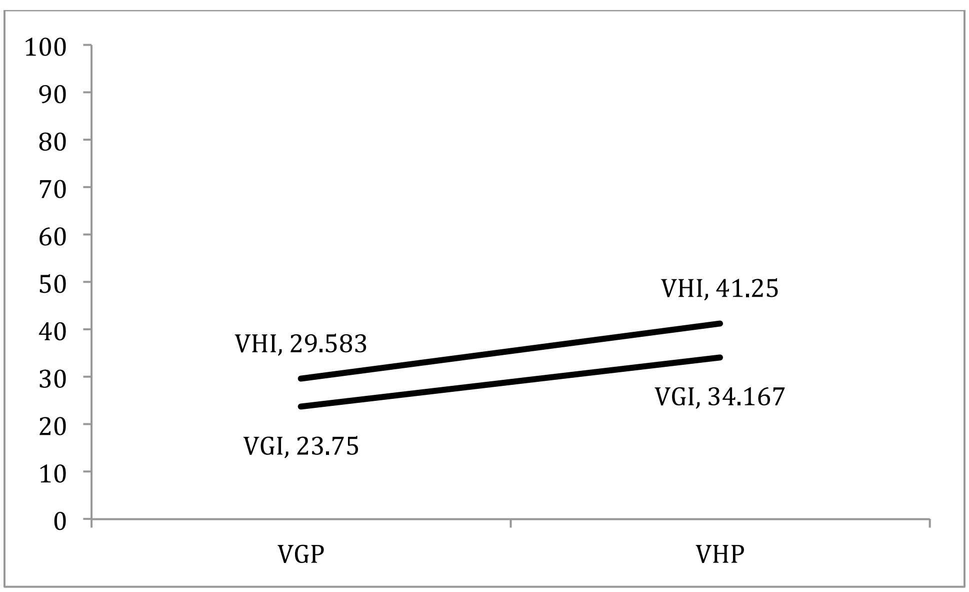

Figure 7: Participants' gain scores for the basic physics system – profile plot.

Table 6: Participants' gain scores for the basic physics system – ANOVA

Source	df	MS	F	P	η^2
Types of Priming	**1**	**2926.042**	**28.324**	**0.000***	**0.22**
Types of Instruction	**1**	**1001.042**	**9.690**	**0.002***	**0.07**
Type of Priming x Type of Instruction	3	9.375	0.091	0.764	0.00
Error	92	103.306			

*p < 0.05
R Squared = 0.293 (Adjusted R Squared = 0.270)

Transfer Scores for the Advanced Physics System (DV2)

Participants' transfer scores demonstrated their performance on the advanced physics system. The participants' mean transfer scores for the advanced physics system are presented in Table 7 and the profile plot for the transfer scores is presented in Figure 8. The result from analysis of variance (ANOVA) is presented in Table 8.

Table 7: Participants' transfer scores for the advanced physics system – mean table

		Types of priming		Total
		VGP	VHP	
Types of instruction	VGI	N = 24 M = 44.458 SD = 7.211	N = 24 M = 51.667 SD = 8.145	N = 48 M = 48.125 SD = 8.419
	VHI	N = 24 M = 52.083 SD = 5.882	N = 24 M = 52.500 SD = 8.470	N = 48 M = 52.292 SD = 7.217
Total		N = 48 M = 48.333 SD = 7.532	N = 48 M = 52.083 SD = 8.241	N = 96 M = 50.208 SD = 8.076

(Scores in percentage)

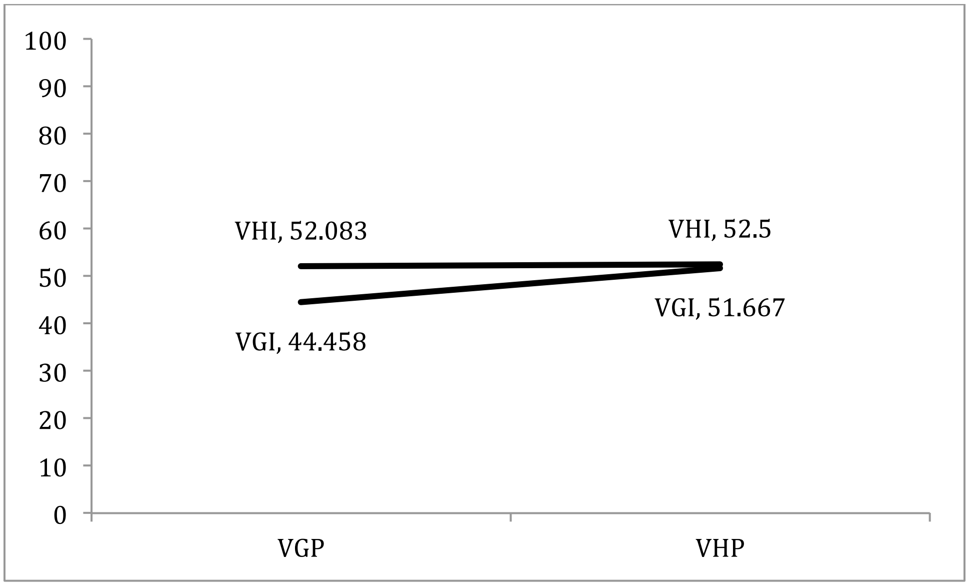

Figure 8: Participants' transfer scores for the advanced physics system – profile plot.

Table 8: Participants' transfer scores for the advanced physics system – ANOVA

Source	df	MS	F	P	η^2
Types of Priming	**1**	**337.500**	**6.000**	**0.016***	**0.05**
Types of Instruction	**1**	**416.667**	**7.407**	**0.008***	**0.07**
Type of Priming x Type of Instruction	**3**	**266.667**	**4.741**	**0.032***	**0.04**
Error	92	56.250			

*p < 0.05
R Squared = 0.165 (Adjusted R Squared = 0.138)

Gain Scores between Misconception Tests (DV3)

The participants' gain scores for the misconception test was represented by the difference between their scores on misconception test 1 and misconception test 2 (i.e. misconception test 2 – misconception test 1). Participants' mean gain scores between physics misconception tests are presented in Table 9 and the profile plot for the gain scores is presented in Figure 9. The result from analysis of variance (ANOVA) is presented in Table 10.

Table 9: Participants' gain scores between the misconception tests – mean table

		Types of priming		Total
		VGP	VHP	
Types of instruction	VGI	N = 24 M = 12.222 SD = 5.170	N = 24 M = 18.750 SD = 3.909	N = 48 M = 15.486 SD = 5.607
	VHI	N = 24 M = 18.889 SD = 5.354	N = 24 M = 19.861 SD = 5.427	N = 48 M = 19.375 SD = 5.355
Total		N = 48 M = 15.556 SD = 6.201	N = 48 M = 19.306 SD = 4.712	N = 96 M = 17.431 SD = 5.793

(Scores in percentage)

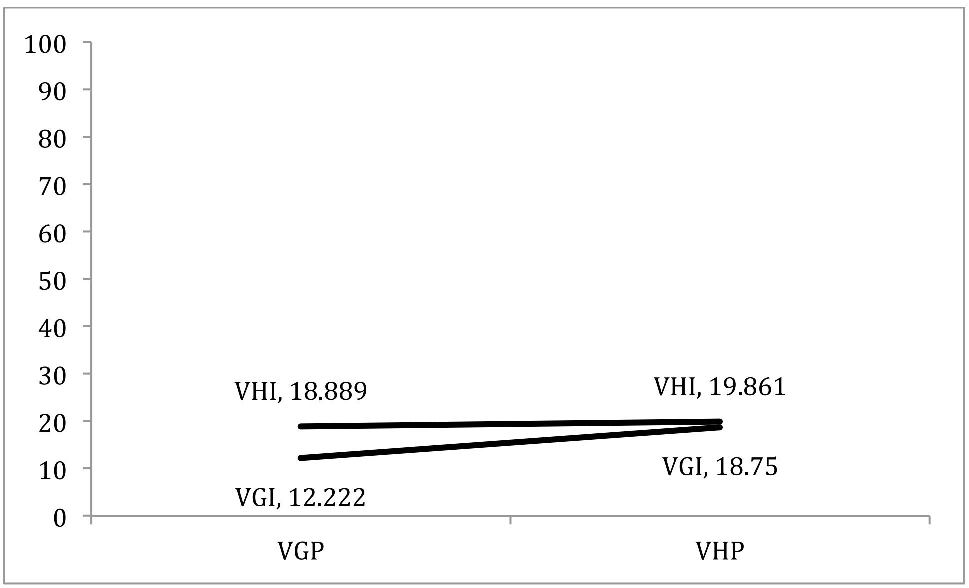

Figure 9: Participants' gain scores between the misconception tests – profile plot.

Table 10: Participants' gain scores between the misconception tests – ANOVA

Source	df	MS	F	P	η^2
Types of Priming	**1**	**337.500**	**13.484**	**0.000***	**0.11**
Types of Instruction	**1**	**185.185**	**7.398**	**0.008***	**0.11**
Type of Priming x Type of Instruction	**3**	**326.963**	**14.501**	**0.000***	**0.03**
Error	92	25.030			

*$p < 0.05$
R Squared = 0.278 (Adjusted R Squared = 0.254)

H1: Visuo-Haptic Priming Has a Significant Effect

To test whether participants who received visuo-haptic priming (VHP) had significantly higher gain scores for the basic physics system, significantly better transfer scores for the advanced physics system, and significantly higher gain scores for the misconception tests than those who received visuo-gestural priming (VGP), a two-way ANOVA was conducted on each of the DV1, DV2, and DV3 variables. The results from the two-way ANOVA showed that:

- Participants who received visuo-haptic priming (VHP) had significantly higher gain scores in the basic physics system than those who received visuo-gestural priming (VGP), $F(1, 92) = 28.32$, $p < 0.001$, $\eta^2 = 0.22$.
- Participants who received visuo-haptic priming (VHP) had significantly better transfer performance than those who received visuo-gestural priming (VGP), $F(1, 92) = 6.00$, $p = .016$, $\eta^2 = 0.05$.
- Participants who received visuo-haptic priming (VHP) had significantly higher gain scores between misconception tests than those who received visuo-gestural priming (VGP), $F(1, 92) = 13.48$, $p < .001$, $\eta^2 = 0.11$.

These findings confirmed that participants who received visuo-haptic priming (VHP) constructed a significantly better mental model for the basic physics system than those who received visuo-gestural priming (VGP).

H2: Visuo-Haptic Instruction Has a Significant Effect

To test whether participants who received visuo-haptic instruction (VHI) had significantly higher gain scores for the basic physics system, significantly better transfer scores for the advanced physics system, and significantly higher gain scores for the misconception tests than those who received visuo-gestural instruction (VGI), a two-way ANOVA was conducted on each of the DV1, DV2, and DV3 variables. The results from the two-way ANOVA showed that:

- Participants who received visuo-haptic instruction (VHI) had significantly higher gain scores in the basic physics system than those who received visuo-gestural instruction (VGI), $F(1, 92) = 9.69$, $p = 0.002$, $\eta^2 = 0.07$.
- Participants who received visuo-haptic instruction (VHI) had significantly better transfer performance than those who received visuo-gestural instruction (VGI), $F(1, 92) = 7.41$, $p = 0.008$, $\eta^2 = 0.07$.
- Participants who received visuo-haptic priming (VHI) had significantly higher gain scores between misconception tests than those who received visuo-gestural instruction (VGI), $F(1, 92) = 14.5$, $p < 0.001$, $\eta^2 = 0.11$.

These findings confirmed that participants who received visuo-haptic instruction (VHI) constructed a significantly better mental model for the basic physics system than those who received visuo-gestural instruction (VGI).

H3: Interaction between Types of Priming and Types of Instruction

To test whether participants who received visuo-haptic simulation in both priming and instruction (VHP-VHI) did not have significantly higher gain scores for the basic physics concept, transfer scores for the advanced physics concept, and gain scores for the misconception tests than those who received visuo-haptic simulation in only priming

(VHP-VGI) or instruction (VGP-VHI), a two-way ANOVA was conducted on each of the DV1, DV2, and DV3 variables. The results from the two-way ANOVA showed that:

- There was no significant interaction between types of priming and types of instruction for participants' gain scores for the basic physics system, $F(3, 92) = 0.09$, $p = 0.764$, $\eta^2 < 0.01$.
- There was a significant interaction between types of priming and types of instruction for participants' transfer performance, $F(3, 92) = 4.74$, $p = 0.032$, $\eta^2 = 0.04$.
- There was a significant interaction between types of priming and types of instruction for participants' gain scores for the misconception tests, $F(3, 92) = 7.40$, $p = 0.008$, $\eta^2 = 0.03$.

Further examination of the significant interaction for the transfer performance using pairwise comparisons revealed that:

- Transfer performance for participants who only experienced visuo-haptic simulation in priming condition (VHP-VGI) and participants who only experienced visuo-haptic simulation in instruction condition (VGP-VHI) were not significantly different, $t(46) = 0.200$, $p = 0.840$.
- Transfer performance for participants who only experienced visuo-haptic simulation in the priming condition (VHP-VGI) and participants who experienced visuo-haptic simulation in both the priming and instruction conditions (VHP-VHI) were not significantly different, $t(46) = 0.350$, $p = 0.730$.
- Transfer performance for participants who only experienced visuo-haptic simulation in the instruction condition (VGP-VHI) and participants who experienced

visuo-haptic simulation in both the priming and instruction conditions (VHP-VHI) were not significantly different, t (46) = 0.200, p = 0.844.

Further examination of the significant interaction for the gain scores between the misconception tests using pairwise comparisons revealed that:

- Gain scores between the misconception tests for participants who only experienced visuo-haptic simulation in the priming condition (VHP-VGI) and participants who only experienced visuo-haptic simulation in the instruction condition (VGP-VHI) were not significantly different, t (46) = 0.103, p = 0.919.
- Gain scores between misconception tests for participants who only experienced visuo-haptic simulation in the priming condition (VHP-VGI) and participants who experienced visuo-haptic simulation in both the priming and instruction conditions (VHP-VHI) were not significantly different, t (46) = 0.814, p = 0.420.
- Gain scores between misconception tests for participants who only experienced visuo-haptic simulation in the instruction condition (VGP-VHI) and participants who experienced visuo-haptic simulation in both the priming and instruction conditions (VHP-VHI) were not significantly different, t (46) = 0.625, p = 0.535.

These findings confirmed that participants who received visuo-haptic simulation in both priming and instruction (VHP-VHI) did not have a significantly higher transfer performance and gain scores for the misconception test than those who only received visuo-haptic simulation in priming (VHP-VGI) or instruction (VGP-VHI). These findings also revealed that in a learning activity, the effects of visuo-haptic priming and visuo-haptic instruction appear additive when participants were exposed to the condition that included both modes of applications (i.e. VHP-VHI).

H4: Visuo-Haptic Priming Has a Significantly Greater Contribution than Visuo-Haptic Instruction

To test whether visuo-haptic priming (VHP) resulted in a more significant contribution to participants' gain scores for the basic physics system and their transfer performance for the advanced physics system than visuo-haptic instruction (VHI), both effect sizes and two-way ANOVAs contrasting between the VHP-VGI and VGP-VHI conditions were used.

As regards participants' gain scores for the basic physics system:

- Visuo-haptic priming had a larger effect size ($\eta^2 = 0.22$) than visuo-haptic instruction ($\eta^2 = 0.05$).
- The contrast estimate = 5.833, indicated that the improvement in gain scores for the basic physics system from visuo-haptic priming was 2.917% more when compared to visuo-haptic instruction. This difference was significant, $F(1, 92) = 6.723$, $p = 0.011$, $\eta^2 = 0.07$.

Regarding participants' transfer performance:

- Visuo-haptic instruction had a larger effect size ($\eta^2 = 0.07$) than visuo-haptic priming ($\eta^2 = 0.05$). The interaction had an effect size of $\eta^2 = 0.05$.
- The contrast estimate = -.417, which indicated that the improvement in transfer performance obtained from visuo-haptic priming was 0.209% lower than that obtained from visuo-haptic instruction. This difference was not significant, $F(1, 92) = 0.037$, $p = 0.848$, $\eta^2 < 0.01$.

These findings confirmed that visuo-haptic simulation in priming (VHP), when compared to visuo-haptic simulation in the instruction stage (VHI), only made a more significant contribution to the participants' gain scores for the basic physics system.

Secondary Analysis: Conceptual and Numerical Understanding

A secondary analysis was conducted concerning the participants' performance in the conceptual component and the numerical component of the gain scores for the basic physics system and transfer performance. This secondary analysis revealed some interesting findings. Participants' mean conceptual problems scores for the pretest, posttest 1, posttest 2, and the transfer test are shown in Figure 10.

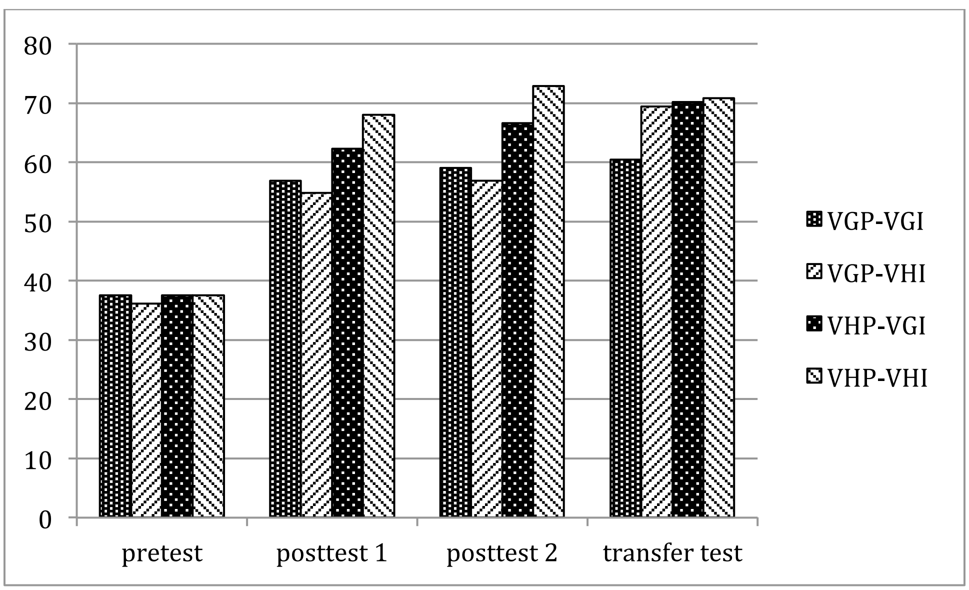

Figure 10: Participants mean conceptual problem scores for the pretest, posttest 1, posttest 2, and the transfer test.

There was no significant difference between the mean conceptual pretest scores for each group, $F(3, 92) = 0.104$, $p = 0.957$, $\eta^2 < 0.01$. This indicated that all participants had similar amounts of conceptual understanding as regards the basic physics system. However, participants' mean conceptual gain scores (Table 11) revealed that participants performed differently according to the conditions they received (Figure 11). Analysis of variance (Table 12) revealed that there was no significant interaction between types of priming and types of instruction as regards the conceptual gain scores for the basic system, $F(3, 92) = 2.057$, $p = 0.155$, $\eta^2 = 0.02$. Participants who received visuo-haptic priming had significantly higher conceptual gain scores for the basic physics system than those who received visuo-gestural priming, $F(1, 92) = 21.066$, $p < .05$, $\eta^2 = 0.18$. At the same time, participants who received visuo-haptic instruction did not have significantly different conceptual gain scores for the basic physics system than those who received visuo-gestural instruction, $F(1, 92) = 1.317$, $p = .254$, $\eta^2 = 0.01$. This finding revealed that only visuo-haptic priming was effective in promoting participants' conceptual understanding of Newton's second law of motion.

Table 11: Participants' conceptual gain scores for the basic physics system – mean table

		Types of priming		Total
		VGP	VHP	
Types of instruction	VGI	N = 24 M = 21.528 SD = 9.167	N = 24 M = 29.167 SD = 12.287	N = 48 M = 25.347 SD = 11.397
	VHI	N = 24 M = 20.833 SD = 12.287	N = 24 M = 35.417 SD = 13.290	N = 48 M = 28.125 SD = 14.650
Total		N = 48 M = 21.181 SD = 10.730	N = 48 M = 32.292 SD = 13.049	N = 96 M = 26.736 SD = 13.130

(Scores in percentage)

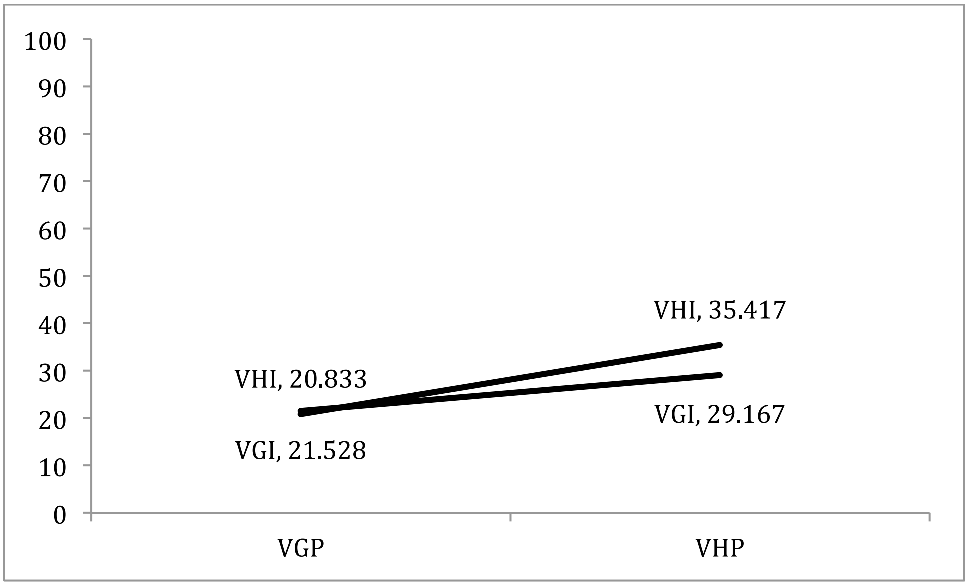

Figure 11: Participants' conceptual gain scores for the basic physics system – profile plot.

Table 12: Participants' conceptual gain scores for the basic physics system – ANOVA

Source	df	MS	F	P	η^2
Types of Priming	**1**	**2962.963**	**21.066**	**0.000***	**0.18**
Types of Instruction	1	185.185	1.317	0.254	0.01
Type of Priming x Type of Instruction	3	289.352	2.057	0.155	0.02
Error	92	140.650			

*p < 0.05
R Squared = 0.210 (Adjusted R Squared = 0.184)

Additionally, participants' mean conceptual transfer scores (Table 13) revealed that participants performed differently according to the test conditions they experienced (Figure 12). Analysis of variance (Table 14) revealed that there was no significant interaction between types of priming and types of instruction as regards the conceptual transfer scores, F (3, 92) = 3.501, p = 0.065, η^2 = 0.03. Participants who received visuo-haptic priming had significantly better conceptual transfer scores than those who received visuo-gestural priming, F (1, 92) = 6.224 p = 0.014, η^2 = 0.06. At the same time, participants who received visuo-haptic instruction also had significantly better conceptual transfer scores than those who received visuo-gestural instruction, $F (1, 92) = 4.765$, $p = 0.032$, $\eta^2 = 0.04$. This finding revealed that both visuo-haptic priming and visuo-haptic instruction were effective in promoting participants' conceptual understanding of Newton's law of universal gravitation.

Table 13: Participants' conceptual transfer scores – mean table

		Types of priming		Total
		VGP	VHP	
Types of instruction	VGI	N = 24 M = 60.417 SD = 11.849	N = 24 M = 70.139 SD = 10.967	N = 48 M = 65.278 SD = 12.316
	VHI	N = 24 M = 69.444 SD = 9.411	N = 24 M = 70.833 SD = 11.261	N = 48 M = 70.139 SD = 10.290
Total		N = 48 M = 64.931 SD = 11.526	N = 48 M = 70.486 SD = 11.002	N = 96 M = 67.708 SD = 11.550

(Scores in percentage)

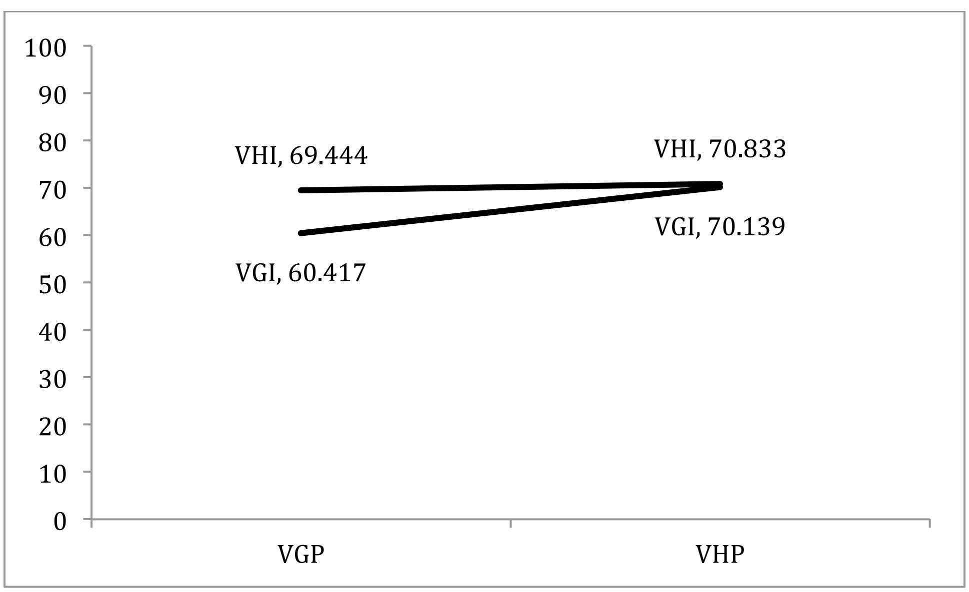

Figure 12: Participants' conceptual transfer scores – profile plot.

Table 14: Participants' conceptual transfer scores – ANOVA

Source	df	MS	F	P	η^2
Types of Priming	**1**	**740.741**	**6.224**	**0.014***	**0.06**
Types of Instruction	**1**	**567.130**	**4.765**	**0.032***	**0.04**
Type of Priming x Type of Instruction	3	416.667	3.501	0.065	0.03
Error	92	119.012			

*p < 0.05
R Squared = 0.136 (Adjusted R Squared = 0.108)

Participants mean numerical problems scores for the pretest, posttest 1, and posttest 2, and the transfer test are shown in Figure 13.

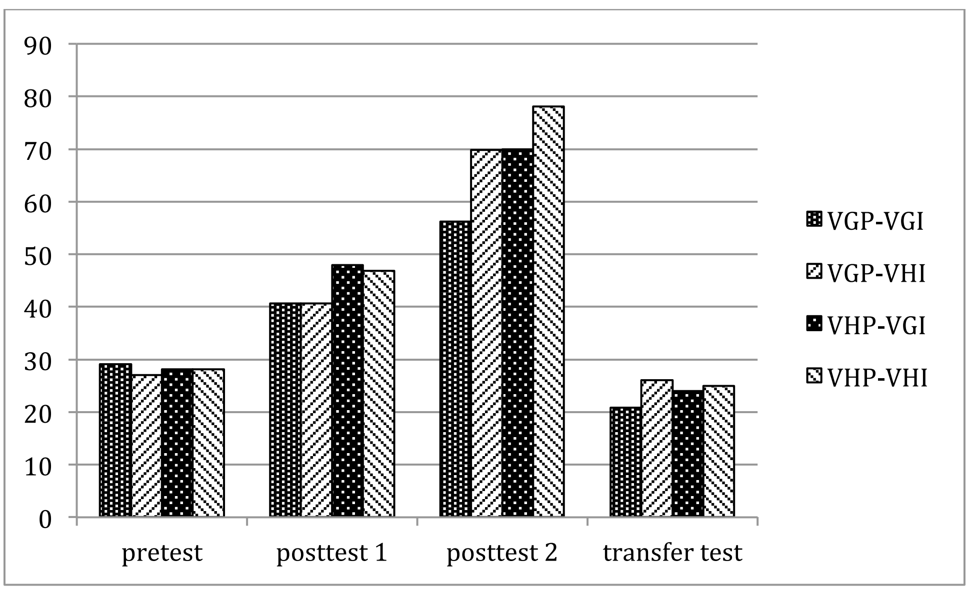

Figure 13: Participants mean numerical problem scores for the pretest, posttest 1, posttest 2, and the transfer test.

There was no significant difference between the numerical pretest scores for each group, $F(3, 92) = 0.042$, $p = 0.988$, $\eta^2 < 0.01$. This indicated that all participants had similar degrees of numerical understanding of the basic physics system. However, participants' mean numerical gain scores (Table 15) revealed that participants performed differently according to the testing conditions received (Figure 14). Analysis of variance (Table 16) revealed that there was no significant interaction between types of priming and types of instruction as regards the participants' numerical gain scores for the basic physics system, $F(3, 92) = 0.634$, $p = 0.428$, $\eta^2 < 0.01$. Participants who received visuo-haptic priming had significantly better numerical gain scores for the basic physics system when compared to those who received visuo-gestural priming, $F(1, 92) = 5.702$, $p = 0.019$, $\eta^2 = 0.05$. At the same time, participants who received visuo-haptic instruction had significantly better numerical gain scores for the basic physics system than those who received visuo-gestural instruction, $F(1, 92) = 6.839$, $p = 0.010$, $\eta^2 = 0.07$. This finding revealed that both visuo-haptic priming and visuo-haptic instruction were effective in promoting participants' numerical understanding of Newton's second law of motion.

Table 15: Participants' numerical gain scores for the basic physics system – mean table

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="2">Types of priming</td><td rowspan="2">Total</td></tr>
<tr><td>VGP</td><td>VHP</td></tr>
<tr><td rowspan="2">Types of instruction</td><td>VGI</td><td>N = 24
M = 27.083
SD = 17.932</td><td>N = 24
M = 41.667
SD = 20.412</td><td>N = 48
M = 34.375
SD = 20.385</td></tr>
<tr><td>VHI</td><td>N = 24
M = 42.708
SD = 26.043</td><td>N = 24
M = 50.000
SD = 24.450</td><td>N = 48
M = 46.354
SD = 25.259</td></tr>
<tr><td colspan="2">Total</td><td>N = 48
M = 34.896
SD = 23.486</td><td>N = 48
M = 45.833
SD = 22.676</td><td>N = 96
M = 40.365
SD = 23.611</td></tr>
</table>

(Scores in percentage)

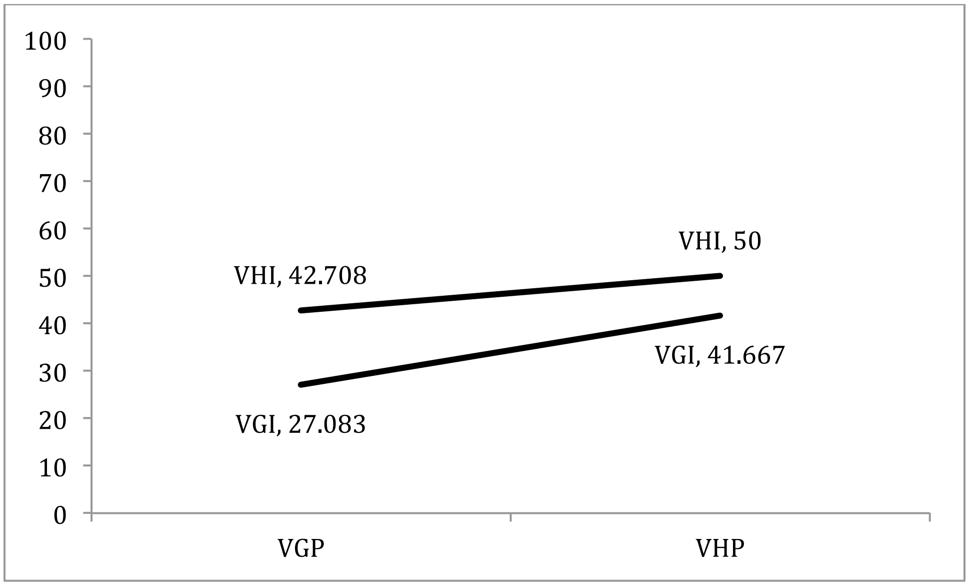

Figure 14: Participants' numerical gain scores for the basic physic system – profile plot.

Table 16: Participants' numerical gain scores for the basic physics system – ANOVA

Source	df	MS	F	P	η^2
Types of Priming	**1**	**2871.094**	**6.839**	**0.010***	**0.07**
Types of Instruction	**1**	**3444.010**	**5.702**	**0.019***	**0.05**
Type of Priming x Type of Instruction	3	319.010	0.634	0.428	0.00
Error	92	503.567			

*p < 0.05
R Squared = 0.125 (Adjusted R Squared = 0.097)

Additionally, participants' mean numerical transfer scores (Table 17) revealed that participants did not perform differently according to the conditions they received (Figure 15). Analysis of variance (Table 18) revealed that there was no significant interaction between types of priming and types of instruction as regards the participants' numerical transfer scores, $F(3, 92) = 0.461$, $p = 0.499$, $\eta^2 < 0.01$. Participants who received visuo-haptic priming did not have significantly different transfer scores than those who received visuo-gestural priming, $F(1, 92) = 0.115$, $p = 0.735$, $\eta^2 < 0.01$. At the same time, participants who received visuo-haptic instruction also did not have significantly different transfer scores than those who received visuo-gestural instruction, $F (1, 92) = 1.038$, $p = 0.311$, $\eta^2 = 0.01$. This finding revealed that neither visuo-haptic priming nor visuo-haptic instruction were effective in promoting participants' numerical understanding of Newton's law of universal gravitation.

Table 17: Participants' numerical transfer scores – mean table

		Types of priming		Total
		VGP	VHP	
Types of instruction	VGI	N = 24 M = 20.833 SD = 14.116	N = 24 M = 23.958 SD = 17.256	N = 48 M = 22.396 SD = 15.676
	VHI	N = 24 M = 26.042 SD = 13.751	N = 24 M = 25.000 SD = 15.887	N = 48 M = 25.521 SD = 14.114
Total		N = 48 M = 23.438 SD = 14.035	N = 48 M = 24.479 SD = 15.887	N = 96 M = 23.958 SD = 14.919

(Scores in percentage)

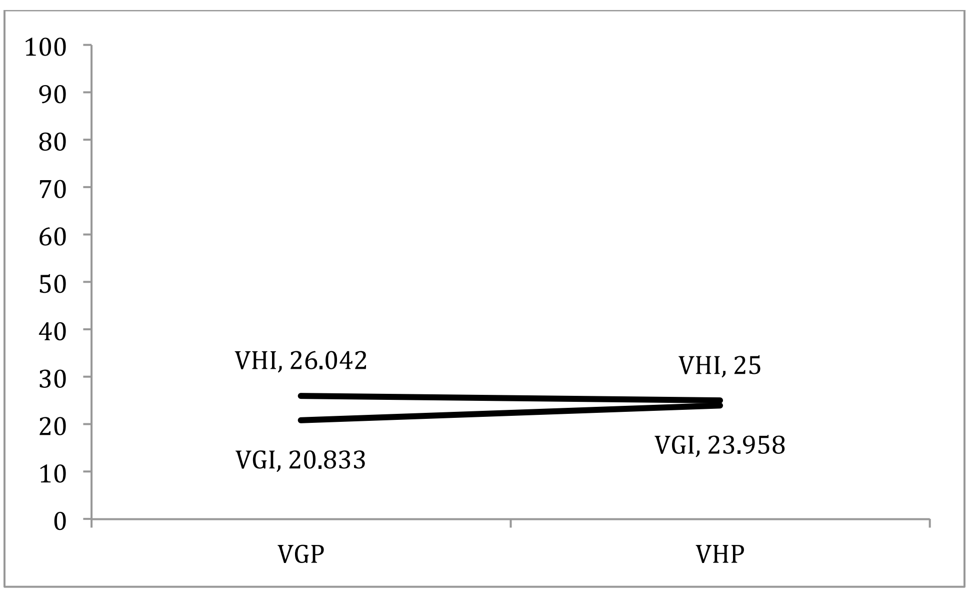

Figure 15: Participants' numerical transfer scores – profile plot.

Table 18: Participants' numerical transfer scores – ANOVA

Source	df	MS	F	P	η^2
Types of Priming	1	26.042	0.115	0.735	0.07
Types of Instruction	1	234.375	1.038	0.311	0.00
Type of Priming x Type of Instruction	3	104.167	0.461	0.499	0.00
Error	92	225.883			

*$p < 0.05$
R Squared = 0.017 (Adjusted R Squared = - 0.015)

In summary, these findings described above revealed that:

(1) Visuo-haptic priming promoted both conceptual understanding and numerical understanding of Newton's second law of motion.

(2) Visuo-haptic instruction only promoted numerical understanding of Newton's second law of motion.

(3) Both visuo-haptic priming and visuo-haptic instruction promoted conceptual understanding of Newton's law of universal gravitation.

(4) Neither visuo-haptic priming nor visuo-haptic instruction promoted numerical understanding of Newton' law of universal gravitation.

After considering the function of visuo-haptic priming and visuo-haptic instruction in mental model construction, several conclusions were drawn:

(1) When participants received visuo-haptic priming, their germane cognitive load was promoted and their extraneous cognitive load was reduced. Therefore, when participants' were primed with visuo-haptic simulation, their prior experiences were activated to help participants' conceptual understanding of how physics concepts in the basic physics system related to each other. At the same time, their prior experience cued them to weed out useless information and to focus on the important

information in the catapult simulation, which was the numerical value of force and mass, and they also achieved better numerical understanding.

(2) When participants received visuo-haptic instruction, their extraneous cognitive load was reduced by off-loading the information process demands from the visual modality to the haptic modality. In this process, participants off-loaded their visual processing demand in reference to the numerical values of force and mass to the haptic process, and they felt those numerical differences through the Novint Falcon. Therefore, participants achieved a better numerical understanding.

(3) In the transfer activity, visuo-haptic priming and visuo-haptic instruction both occurred prior to the transfer task. Therefore, both visuo-haptic priming and visuo-haptic instruction became priming conditions for the transfer task. However, the advanced physics systems in the transfer task included more physics concepts and the inverse square law. This complexity disallowed participants to successfully determine which information was useless. As a result, they were unable to weed out useless information and this affected their numerical understanding. Therefore, participants who had any types of visuo-haptic simulation prior to the transfer activity had a significantly better conceptual understanding of the task, but did not have a significantly different numerical understanding.

Interview data

In addition to results from the data analysis, selected responses to the exit interview questions provided more insight into the participants' experience.

Interview Question 1

Interview question 1 asked participants if they learned something new about physics from this learning experience. 59% of participants reported that they did not learn something new about physics (Table 19). Interestingly, 78% of participants who claimed that they did not learn something new revealed in their explanation that they were reminded about the functional relations between physics concepts. For example, one participant in the VHP-VGI condition said that:

> "I don't think I got any new ideas from this because I knew about force and all. But I think this experience help me remembered how mass and force work together to move things faster or slower."

Table 19: Descriptive data for participants' responses to interview question 1

Condition (n)	% Learned something new (n)	% Didn't learn something new (n)	% Declined to answer (n)
VGP-VGI (24)	13% (3)	67% (16)	21% (5)
VGP-VHI (24)	21% (5)	54% (13)	25% (6)
VHP-VGI (24)	25% (6)	58% (14)	17% (4)
VHP-VHI (24)	21% (5)	58% (14)	21% (5)
Total (96)	**19% (18)**	**59% (57)**	**22% (20)**

Interview Question 2

Interview question 2 asked participants if this learning experience changed what they already knew about physics. 62% of participants reported that this learning experience changed what they knew about physics (Table 20). Additionally, 52% of participants who believed that this learning experience changed what they knew about physics revealed that this learning experience helped them with acquiring additional knowledge in reference to the numerical relations between physics concepts. One participant in VGP-VHI condition said that:

> "I always knew you need to put a lot more force in your arm to throw something heavier at the same speed. I didn't know that they are 1-to-1 ratio though. It kind of made me think more on how different force and mass works."

Table 20: Descriptive data for participants' responses to interview question 2

Condition (n)	% Change in knowledge (n)	% Didn't change in knowledge (n)	% Declined to answer (n)
VGP-VGI (24)	58% (14)	17% (4)	25% (6)
VGP-VHI (24)	63% (15)	25% (6)	13% (3)
VHP-VGI (24)	58% (14)	21% (5)	21% (5)
VHP-VHI (24)	71% (17)	13% (3)	17% (4)
Total (96)	**62% (60)**	**19% (18)**	**19% (18)**

Interview Question 3

Interview question 3 asked participants which part of this learning experience is the most useful in helping them learn about physics. Participants' response varied by group (Table 21). Participants in the VGP-VGI condition generally considered that priming (42%)

and instruction (46%) were the most useful application. 71% of the participants in the VGP-VHI conditions considered visuo-haptic instruction was the most useful application. 71% of the participants in the VHP-VGI and 54% of the participants in VHP-VHI condition thought visuo-haptic priming was the most useful application. According to one participant in the VHP-VHI condition:

> "The First game was more fun and useful. Plus I kind of knew about force and mass after the first game. The second game did a little to me. Maybe just how each force and mass felt different, that's all."

Table 21: Descriptive data for participants' responses to interview question 3

Condition (n)	% Sling shot in priming (n)	% Catapult in instruction (n)	% Gravity in transfer (n)	% Declined to answer (n)
VGP-VGI (24)	42% (10)	46% (11)	8% (2)	4% (1)
VGP-VHI (24)	8% (2)	71% (17)	4% (1)	17% (4)
VHP-VGI (24)	71% (17)	13% (3)	8% (2)	8% (2)
VHP-VHI (24)	54% (13)	29% (7)	17% (4)	0% (0)
Total (96)	**44% (42)**	**40% (38)**	**9% (9)**	**7% (7)**

Interview Question 4

Interview question 4 asked participants how they would teach these concepts to their classmates. For Newton's second law of motion (Table 22), 82% of the participants adopted either the catapult or sling shot as an example. For Newton's law of universal gravitation (Table 23), 46% of the participants who received any type of visuo-haptic representation used their hands and simulated the change in gravitational force between two objects based on the distance in between. One participant in the VHP-VHI condition said that:

> "I think this is a good way to show them how it works. They probably not

gonna feel the force, but I will tell them to imagine that it gets less and less as your hands are more and more apart."

Table 22: Descriptive data for participants' responses to interview question 4 – Newton's second law of motion

Condition (n)	% Use sling shot (n)	% Use catapult (n)	% Use formula (n)	% Declined to answer (n)
VGP-VGI (24)	38% (9)	46% (11)	17% (4)	0% (0)
VGP-VHI (24)	33% (8)	42% (10)	17% (4)	8% (2)
VHP-VGI (24)	50% (12)	33% (8)	8% (2)	8% (2)
VHP-VHI (24)	54% (13)	29% (7)	13% (3)	4% (1)
Total (96)	**44% (42)**	**38% (36)**	**14% (13)**	**5% (5)**

Table 23: Descriptive data for participants' response to interview question 4 – Newton's law of universal gravitation

Condition (n)	% Use hand gestures (n)	% Use formula (n)	% Other method (n)	% Declined to answer (n)
VGP-VGI (24)	38% (9)	13% (3)	17% (4)	33% (8)
VGP-VHI (24)	33% (10)	8% (2)	21% (5)	29% (7)
VHP-VGI (24)	54% (13)	13% (3)	21% (5)	13% (3)
VHP-VHI (24)	54% (13)	8% (2)	25% (6)	13% (3)
Total (96)	**46% (42)**	**11% (10)**	**21% (20)**	**22% (21)**

Summary

Findings from the dissertation study confirmed most of the hypotheses for this dissertation. In summary, I concluded that visuo-haptic simulation was significantly more effective in promoting mental model construction than visuo-gestural simulation. Mental models constructed through visuo-haptic simulation not only helped participants to reach a higher level of understanding for the basic physics system in the learning activity, but also helped participants to reach a higher level of understanding for the advanced physics system in the transfer activity. Visuo-haptic simulation was also significantly more effective in remedying participants' physics misconception than visuo-gestural simulation. However, it is worth noting that participants' final misconception test performance was still below FCI's entry-level threshold of 60%.

In addition, visuo-haptic priming was significantly more effective than visuo-haptic instruction in promoting participants' mental model construction during the learning activity. However, visuo-haptic instruction was more effective in helping participants construct a mental model of the transfer activity. Since the visuo-haptic instruction took place immediately before the transfer activity, this could also have served as a visuo-haptic priming strategy for the transfer task. Therefore, I concluded that visuo-haptic priming is significantly more effective in mental model construction than visuo-haptic instruction.

Finally, visuo-haptic priming and visuo-haptic instruction demonstrated a negative interaction for the transfer task and the misconception tests. Since both visuo-haptic priming and visuo-haptic instruction occurred prior to the transfer task and misconception test 2, both visuo-haptic priming and visuo-haptic instruction can be considered as the priming mechanism used for the later tasks. Based on the data analysis and pairwise comparison, I concluded that the effects of visuo-haptic priming alone (VHP-VGI), visuo-haptic instruction alone (VGP-VHI), and both visuo haptic priming and instruction applied together (VHP-VHI) were indistinguishable in influencing the transfer task and misconception test 2.

The only failed hypothesis revealed perhaps the most interesting finding for this dissertation. Visuo-haptic priming and visuo-haptic instruction did not any interaction for the basic physics system's gain scores. Instead, they had an additive effect. This indicated that visuo-haptic priming and visuo-haptic instruction independently affected participants' mental model construction. The secondary data analysis on question types as well as the responses to the exit interview provided further insight into this result. Generally speaking, participants who received visuo-haptic priming reported that it reminded them of the causal relations between physics concepts. Participants who receive visuo-haptic instruction, alternatively, reported that visuo-haptic instruction helped them to understand how different values of force and mass related to acceleration. Therefore, I concluded that while visuo-haptic priming more particularly helped participants' conceptual understanding, visuo-haptic instruction helped participants' numerical understanding. In short, the effect of visuo-haptic priming and visuo-haptic instruction were realized through in different modes of understanding.

Chapter V

DISCUSSION

In this dissertation, I investigated the potential of visuo-haptic simulation over visuo-gestural simulation in resolving mental model construction constraints. More specifically, I examined the role of somatosensory information, an important component of visuo-haptic simulation, and different applications of visuo-haptic simulation in improving participants' mental model construction. Consolidating findings from the pilot study and the dissertation study, I concluded that:

(1) While both visuo-haptic and visuo-gestural simulations were effective in mental model construction for physics systems, visuo-haptic simulation was significantly more effective in promoting mental model construction. In this dissertation, visuo-haptic simulation helped participants to both reach a higher level of understanding for the basic physics system and achieve a better transfer to the advanced physics system. This result confirmed the overall structure of the grounded learning experience framework.

(2) Visuo-haptic simulation was significantly more effective in remedying participants' physics misconceptions than visuo-gestural simulation. Participants' physics misconceptions were rooted in their prior knowledge, which can be considered as their existing schemas. By remedying participants' physics misconceptions, visuo-haptic simulation updated their schemas and promoted schema acquisition to help them learn new knowledge. This finding revealed that

when participants had misconceptions, their prior experiences were more useful than their prior knowledge in helping them learn new knowledge.

(3) During the learning activity, visuo-haptic priming was more effective than visuo-haptic instruction in promoting participants' mental model construction. For the transfer activity, visuo-haptic instruction in previous learning activity also became a priming condition. As a result, visuo-haptic instruction can be considered as a near-priming condition while the earlier visuo-haptic priming can be considered as a far-priming condition for the transfer activity. The effects of near- and far-priming conditions on participants' mental model construction of the transfer activity were indistinguishable. Collectively, these findings not only suggested the efficacy of visuo-haptic priming in mental model construction, they also implied that the effect of visuo-haptic priming was long lasting. In other words, visuo-haptic priming was still effective even if it was not conducted immediately before learning.

(4) The effects of visuo-haptic simulation in priming alone (VHP-VGI), visuo-haptic simulation in instruction alone (VGP-VHI), and visuo-haptic simulation in priming and instruction (VHP-VHI) on tasks after the learning activity were indistinguishable to each other but were all significantly higher than the effects of visuo-gestural simulation in priming and instruction (VGP-VGI). In other words, when compared to visuo-gestural simulation, visuo-haptic simulation constructed a significantly better mental model as long as it was a part of the learning activity.

(5) Visuo-haptic priming and visuo-haptic instruction promoted different types of understanding. Visuo-haptic priming promoted both conceptual and numerical

understanding of the physics systems. Alternatively, visuo-haptic instruction promoted only numerical understanding of the physics systems. This finding on the grounded learning experience framework implied that the promoted germane cognitive load improved participants' conceptual understanding of the physics systems examined, and the reduced extraneous cognitive load improved their numerical understanding of the physics systems.

Limitations

There were three limitations to this dissertation. First, unnecessary information was given in both the pilot study and the dissertation study. Participants in the pilot study were shown videos on the physics systems to be learned and participants in the dissertation study were given a posttest 1 that was not used in the analysis. Since these studies did not control for participants' visual/verbal/auditory process abilities, some participants might have benefited more from this unnecessary information than others. Therefore, participants' abilities need to be better controlled for and unnecessary information needs to be removed in future or replica studies.

Second, the pilot study and the dissertation studies were both conducted with a specific and traditionally underserved population (community college students enrolled in STEM courses) on a specific domain (physics). As a result, findings from this dissertation may not be generalizable beyond this population and this domain. However, it is possible for future research to replicate the studies in this dissertation for another domain or population.

Third, studies in this dissertation were limited to force concept related physics systems because somatosensory information was only manipulated by the presence of force feedback to the haptic channel. Therefore, findings in this dissertation may not be generalizable beyond force concepts (e.g. temperature). However, future research might consider stimulating somatosensory information in different ways for other physics concepts.

Theoretical Contributions

Findings from this dissertation contribute to the theory of implicit learning, cognitive load theory, and the embodiment perspective. Implicit learning is an emerging and controversial theory that addresses the learning of complex information without explicit awareness of what has been learned (Frensch & Runger, 2003). As a result of implicit learning, learners obtain implicit knowledge in the form of abstract representations rather than verbatim representations. In the dissertation study, participants' learning procedure and outcome can be consider implicit since participants obtained abstract representations of the physics system without receiving any formal instruction. Findings and conclusions from this dissertation demonstrated that priming, an implicit memory effect, significantly contributes to the formation of implicit knowledge during learning. Through priming, people implicitly learned new knowledge with the schemas that were formed by their prior experiences. To summarize priming's contribution to implicit learning, I identified three of its characteristics: first, priming should only contain information that is essential to and directly associated with contents in later learning; second, priming should be delivered in a method that is easy for people to process the information; third, priming is effective even when it is not conducted immediately before content learning. In the case of this dissertation, priming conducted for as long as thirty minutes prior to learning was still effective.

Findings from this dissertation also contribute to cognitive load theory by providing insight on the germane cognitive load. Traditionally, discussions on cognitive load theory have often failed to explain the formation of the germane cognitive load. To this end, de Jong (2010) has criticized germane cognitive load as a post-hoc explanation because one cannot identify it before experimentation. In this dissertation, I explained cognitive load theory using Cowan's (1995) working memory model in additional to Baddeley and Hitch's (1974) multicomponent model of working memory and emphasized the timing of applying visuo-haptic simulation. By understanding how different applications of visuo-haptic simulation affect different types of cognitive load, I identified that the germane cognitive load was promoted through priming people's prior experiences. In other words, the germane cognitive load is formed through prior experience. Therefore, a content knowledge has a high level of germane cognitive load if it is seen or used in people's daily life, and an instruction achieves a high level of germane cognitive load if it activates people's relevant prior experience or if it provides people with a relevant experience before content learning. Moreover, I associated changes in the germane and the extraneous cognitive load to specific types of understanding. Mapping the findings from the dissertation study on the grounded learning experience framework, I stressed that promoting germane cognitive load improves conceptual understanding and reducing extraneous cognitive load improves numerical understanding.

Finally, findings from this dissertation contribute to the embodiment perspective by operationally differentiating grounded and embodied cognition. While both grounded and embodied learning experience focus on people seeing the result of their action, grounded learning experience puts an additional emphasis on people feeling environmental cues in the process. By identifying environmental cues as a key factor in a grounded learning experience and operationalizing it through somatosensory information, I have successfully differentiated the grounded and embodied learning experiences that lead to cognition. Additionally, I filled a void in the research on grounded cognition by explaining the mechanisms behind its formation. I postulate that grounded cognition is formed by having relevant prior experiences connect sensory stimulations with content while eliminate unnecessary information in the content, or by distributing information to different modalities for independent processing.

Practical Implications

Based on findings from this dissertation, I have identified three practical implications in instruction. First, when trying to teach physics conceptually, instruction should begin with relevant examples. These examples should not be generic. Instead, these examples should be dynamic and adapt to students' demographic and interests so that learners can easily relate to these examples. At the same time, when trying to teach physics numerically, instruction should be conducted with minimum distraction. This not only means that students should learn in an environment that is unaffected by visual and audio distractions, it also means that the instructor should avoid using abstract terminologies or abbreviations too early in the instruction process.

Second, laboratory exercises should be conducted before content instruction instead of after. By doing so, laboratory exercises can function as a priming condition for the content to be learned during instruction. If a laboratory exercise is too complex and difficult to comprehend without prior content instruction, the instructor should still try to have students carry out some initial preparation for the laboratory exercise before they receive content instruction so that they can benefit from a priming condition.

Third, unless the particular physics concept or system can only be observed in the laboratory setting or is too dangerous to be independently conducted by students, the instructor should try to have students conduct laboratory exercises by using objects in a setting that are natural to the physics concept or system so that a grounded learning experience can be fully utilized. For example, instead of conducting an aerodynamic exercise in the laboratory setting, instructors should try to have students go outside and fly a kite.

Future Research Direction

There were several future research directions that could further extend the practical implication and theoretical contribution of the grounded learning experience framework. Future research on extending the practical implication of the grounded learning experience framework should consider different populations, generalizability in physics, and generalizability in other STEM domains. First, the current studies focused on community college students. Although the grounded learning experience framework helped this population remedy physic misconceptions and learn about force concept related physics systems, the students' lack of accurate knowledge in physics at the college level suggested that their physics learning difficulties were rooted in their earlier physics knowledge. Since most people start their formal learning of physics in high school, high school students would be an ideal group for this kind of study in future research. Therefore, further research could investigate how high school students' learning and mental model construction for physics systems improve with the grounded learning experience framework. In other words, future research should investigate how the grounded learning experience framework prevents learning difficulties instead of remedying physics misconceptions.

Second, empirical studies in this dissertation only focused on two force concept related physics systems. There are many other physics systems, both simpler and more abstract ones, that utilize force concepts and these could be explored through the grounded learning experience framework. A simpler physics system would be Newton's third law of motion, which simply states that force action and reaction are equal in magnitude and opposite in direction. A more abstract physics system would be electromagnetism, which involves varied numbers of force factors in a three-dimensional space. In addition, there are other physics concepts such as temperature that cannot be simulated through force feedback. Therefore, future research could also consider using other haptic devices to provide different somatosensory information in learning physics systems that are associated with non-force concepts. Together, these studies could provide a more comprehensive understanding of the grounded learning experience framework in its efficacy of fostering general physics learning.

Third, future research could consider expanding the grounded learning experience framework into other STEM (science, technology, engineering, and mathematics) curriculums. Since the instructional application of the grounded learning experience framework implied that a grounded learning experience leads to an improved numerical understanding, mathematics would be an ideal STEM curriculum to use for the expansion of the grounded learning experience framework.

Future research on the theoretical contribution of the grounded learning experience framework should investigate the impact of the length of visuo-haptic priming, understand the effect of incorporating the auditory modality, and compare simulations with real-life exercises. First, future research could investigate the ideal length of application needed for optimizing priming for the purpose of learning. In the dissertation study, I had participants exposed to the priming condition for twenty minutes, which was the same length of time as the instruction condition, to achieve a better control. However, this length of exposure was set arbitrarily and did not imply that twenty minutes was an ideal length of priming. One can assume that the duration and the benefit of priming would initially have a positive linear correlation and eventually level at a certain point of time. Further research should investigate the saturation point in order to gain more insight into implications for visuo-haptic priming.

Second, the grounded learning experience framework did not include the auditory modality. Since the auditory modality is an important part of many studies in multimedia learning (see the cognitive theory of multimedia learning), future research on the grounded learning experience framework should incorporate the auditory modality to better understand the effect of its interactions with visuo-haptic simulation on mental model construction.

Third, the grounded learning experience framework assumed that a visuo-haptic simulation provides people with a realistic experience. However, little was known about how it would compare to a real-life exercise. Would people learn less in a real-life exercise because there would be too much extraneous information, or would they learn more because there would be more useful environmental cues than what were controlled for in a simulation? Future research should compare multimodal simulations to real-life exercises to gain a better understanding on the benefits or drawbacks of using multimodal simulations.

This dissertation serves as the starting point for an initial discussion of the grounded learning experience framework. Findings from this dissertation confirmed the efficacy of this framework in learning about force concept related physics systems. Future research should expand on this framework to further its impact, not only on how people learn about systems, but also on cognitive theories behind learning.

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APPENDIX A: Pretest/Posttest for Pilot Study

1. Which one of the following is a correct form of Newton's second law of motion?
    a. f = mga
    b. m = (h*s)/f
    c. a = f/m
    d. None of the above
2. If the mass of a sliding block is somehow tripled at the same time the force on it is tripled, the acceleration of the block will:
    a. Be the same
    b. Increase
    c. Decrease
    d. None of the above
3. If the force on a sliding block somehow tripled, how will the acceleration change in response?
    a. Not change at all
    b. Increase by 3 times
    c. Decrease by 3 times
    d. None of the above
4. If the mass on a sliding block somehow tripled, how will the acceleration change in response?
    a. Not change at all
    b. Increase by 9 times
    c. Decrease by 9 times
    d. None of the above
5. What is direction of acceleration of a rock at the top of its trajectory , right before it start to fall downwards, when it has been thrown straight upwards?
    a. No acceleration at all
    b. Downwards
    c. Upwards
    d. None of the above
6. Does a falling object increase in speed if its acceleration of fall decreases?
    a. Yes
    b. No
    c. Depends on its mass
    d. None of the above

7. A common saying goes, “It’s not the fall that hurts you; it’s the sudden stop.” In Newton’s second law, that means?
    a. The sudden change in the direction of force hurts you
    b. The sudden change in the direction of acceleration hurts you
    c. Your mass hurts you
    d. None of the above
8. When a car is moving at a constant velocity, the direction of the net force acting on it is?
    a. Forward
    b. Backward
    c. There is no net force
    d. None of the above
9. When a car move forward from rest, the direction of acceleration is?
    a. There is no acceleration
    b. Forward
    c. Backward
    d. None of the above
10. If a piece of heavy rock fall into the truck bed when the truck is moving forward at a constant speed, the truck’s acceleration will be?
    a. Increased
    b. Decreased
    c. Depends on the net force
    d. None of the above

APPENDIX B: Transfer Test for Pilot Study

1. Which one of the following is a correct form of Newton's law of universal gravitation?
    a. f = G*(m1*m2)/d
    b. G = f*(d^2)/ (m1*m2)
    c. d = f*(m1*m2)/G
    d. None of the above
2. What does Newton's law of universal gravitation means for two objects?
    a. With greater distance between them, the force between them increases.
    b. If object 1 increase in mass, the force between them decreases.
    c. If object 2 decrease in mass, the force between them decreases.
    d. None of the above
3. If the mass of object 1 is somehow tripled while the mass of object 2 remain the same, the force between them will:
    a. Be the same
    b. Increase by 3 times
    c. Decrease by 3 times
    d. None of the above
4. If the mass of object 1 is somehow tripled while the mass of object 2 become 1/3 of its original weight, the force between them will:
    a. Not change at all
    b. Increase by 3 times
    c. Decrease by 3 times
    d. None of the above
5. If the distance between object 1 and object 2 tripled, the force between them will?
    a. Not change at all
    b. Increase by 9 times
    c. Decrease by 9 times
    d. None of the above
6. If a small mass object in space is in a close distance with a large planet, what is the direction of force acting on the small mass object?
    a. No force at all
    b. Away from the planet
    c. Towards the planet
    d. None of the above
7. Does gravitational force acts on all bodies in proportion to their masses??
    a. Yes

    b. No
    c. Depends on its G constant
    d. None of the above
8. A statement goes, "When a starship is in between sun and earth at the same distance, sun can pull in you more than earth can" In Newton's law of universal gravitation, that means?
    a. Sun has a larger mass
    b. Earth has a larger mass
    c. You mass is different when you are closer to sun
    d. None of the above
9. When the distance between 2 objects decrease by 2, how does the gravitation force between them change?
    a. Decrease by 2
    b. Increase by 2
    c. It does not change
    d. None of the above
10. Does the gravitational force increase or decrease atop of Mt. Everest than at sea level?
    a. The same
    b. Increase
    c. Decrease
    d. None of the above

APPENDIX C: Pretest for Dissertation Study

ID number: ________________ Date: _____________

1. Which one of the following shows how force, mass and acceleration are related?
   a. $f = m*a$
   b. $f = a/m$
   c. $f = m^2/a$
   d. None of the above
2. Assume that someone is pushing a rock at a constant speed. If the rock suddenly becomes 3 times heavier and the person triples his pushing force, the rock will
   a. move the same speed.
   b. move faster.
   c. move slower.
   d. None of the above
3. Assume that someone is pushing a rock at a constant speed and suddenly triples his pushing force. The rock will
   a. move at the same speed.
   b. move 3 times faster.
   c. move 3 times slower.
   d. None of the above
4. Assume that someone is pushing a rock at a constant speed and the rock suddenly becomes 5 times heavier. The rock will
   a. move at the same speed.
   b. move 10 times faster.
   c. move 10 time slower.
   d. None of the above
5. When a ball is tossed in the air, it slows down as it reaches its highest point. During this time, the rock's mass will
   a. increase.
   b. decrease.
   c. remain the same.
   d. None of the above
6. As a rock falls from the sky and picks up speed, which one of the following does not change?
   a. The mass of the rock
   b. The force acting on the rock
   c. The acceleration of the rock
   d. None of the above

7. Assume that someone is pushing a rock. When he doubles his pushing force, the rock moves 3 times faster. What is a possible explanation?
    a. The mass of the rock is reduced to 25% as he doubles his pushing force
    b. The mass of the rock is reduced to 50% as he doubles his pushing force
    c. The mass of the rock is reduced to 75% as he doubles his pushing force
    d. None of the above
8. When a car is moving at a constant speed, the amount of force acting on the car is
    a. the same.
    b. increasing.
    c. decreasing.
    d. None of the above
9. When a person slows down a car using the brakes, he is
    a. increasing the car's mass.
    b. decreasing the car's mass.
    c. decreasing the car's acceleration.
    d. None of the above
10. Assume that a truck is moving at a constant speed on a flat road. If a heavy rock suddenly falls into the back of the truck, the truck will
    a. Move faster
    b. Move slower
    c. Move at the same speed
    d. None of the above

Appendix D: Posttest 1 for Dissertation Study

ID number: _________________ Date: _____________

1. Which one of the following shows how force, mass and acceleration are related?
   a. $m = f*a^2$
   b. $m = a/f$
   c. $m = f/a$
   d. None of the above
2. Assume that someone is pushing a rock at a constant speed. If the rock suddenly becomes 2 times lighter and the person reduces his pushing force by half, the rock will
   a. move at the same speed.
   b. move faster.
   c. move slower.
   d. None of the above
3. Assume that someone is pushing a rock at a constant speed and suddenly doubles the pushing force. The rock will
   a. move at the same speed.
   b. move 4 times faster.
   c. move 4 times slower.
   d. None of the above
4. Assume that someone is pushing a rock at a constant speed and the rock suddenly become 6 times lighter. The rock will
   a. move at the same speed.
   b. move 6 times faster.
   c. move 6 time slower.
   d. None of the above
5. When a ball is tossed in the air, it speeds up as it falls back down. During this time, the rock's mass will
   a. increase.
   b. decrease.
   c. remain the same.
   d. None of the above
6. Assume that a rock is moving at a constant speed. Which one of the following conditions can slow the rock down?
   a. The mass doubles as the force on the rock doubles
   b. The mass stays constant as the force on the rock doubles
   c. The mass doubles as the force on the rock remains the same
   d. None of the above

7. Assume that someone is pushing a rock. When he doubles his pushing force, the rock moves 5 times faster. What is a possible explanation?
    a. The mass of the rock is reduced by 60% as he doubles his pushing force
    b. The mass of the rock is reduced by 50% as he doubles his pushing force
    c. The mass of the rock is reduced by 40% as he doubles his pushing force
    d. None of the above
8. When a car is moving faster and faster, the amount of force acting on the car is
    a. the same.
    b. increasing.
    c. decreasing.
    d. None of the above
9. When a person speeds up a car, he is
    a. increasing the car's mass.
    b. decreasing the car's mass.
    c. decreasing the car's acceleration.
    d. None of the above
10. Assume that a truck is slowing down on an uphill road. If a heavy rock suddenly falls into the back of the truck, the truck will
    a. move even slower.
    b. move faster.
    c. move at the same speed.
    d. None of the above

Appendix E: Posttest 2 for Dissertation Study

ID number: ________________ Date: _____________

1. Which one of the following shows how force, mass and acceleration are related?
    a. a = f*m
    b. a = m/f
    c. $a = f/m^2$
    d. None of the above
2. Assume that someone is pushing a rock at a constant speed. If the rock suddenly becomes 5 times heavier and the person doubles his pushing force, the rock will
    a. move at the same speed.
    b. move faster.
    c. move slower.
    d. None of the above
3. Assume that someone is pushing a rock at a constant speed and suddenly triples his pushing force. The rock will
    a. move at the same speed.
    b. move 6 times faster.
    c. move 6 times slower.
    d. None of the above
4. Assume that someone is pushing a rock at a constant speed and the rock suddenly become 4 times heavier. The rock will
    a. move at the same speed.
    b. move 2 times faster.
    c. move 2 time slower.
    d. None of the above
5. When a ball is tossed in the air, it is weightless when it reaches the highest point. During this time, the rock's mass will
    a. increase.
    b. decrease.
    c. remain the same.
    d. None of the above
6. Assume that a rock is moving at a constant speed. Which one of the following conditions can increase the speed of the rock?
    a. The mass doubles as the force on the rock doubles
    b. The mass remain the same as the force on the rock doubles
    c. The mass doubles as the force on the rock remains the same
    d. None of the above

7. Assume that someone is pushing a rock. When he doubles his pushing force, the rock remains at the same speed. What is a possible explanation?
    a. The mass of the rock is reduced by 50% as he doubles his pushing force
    b. The mass of the rock is doubled as he doubles his pushing force
    c. The mass of the rock is the same as he doubles his pushing force
    d. None of the above
8. When a car is moving slower and slower, the amount of force acting on the car is
    a. the same.
    b. increasing.
    c. decreasing.
    d. None of the above
9. When a person speeds up a car, he is?
    a. Increasing the car's mass
    b. Decreasing the car's mass
    c. Increasing the car's acceleration
    d. None of the above
10. Assume that a truck that carries a heavy rock is moving faster and faster on an uphill road. If the rock suddenly falls out of the truck, the truck will?
    a. Move even faster
    b. Move slower
    c. Move at the same speed
    d. None of the above

Appendix F: Transfer Test for Dissertation Study

ID number: _________________ Date: _____________

1. Which one of the following shows how force, masses and distance are related in free space?
   a. f = G*(m1*m2)/d
   b. G = f*(d^2)/ (m1*m2)
   c. d = f*(m1*m2)/G
   d. None of the above
2. According to Newton's law of universal gravitation, the force between two objects when they are in free space
   a. increases as the distance between them increases.
   b. decreases as their masses increase.
   c. decreases as their masses decrease.
   d. None of the above
3. Assume that object 1 and 2 are in free space. If object 1's mass triples but object 2's mass remains the same, the force between them will be
   a. the same.
   b. 3 times more.
   c. 3 times less.
   d. None of the above
4. Assume that object 1 and 2 are in free space. If object 1's mass triples but object 2's mass reduces to 1/3, the force between them will be
   a. the same.
   b. 3 times more.
   c. 3 times less.
   d. None of the above
5. Assume that object 1 and 2 are in free space. If the distance between object 1 and object 2 triples, the force between them will be
   a. the same.
   b. 9 times more.
   c. 9 times less.
   d. None of the above
6. If an small object is near a very large planet in free space, the gravitational force acting on the object will point
   a. anywhere.
   b. away from the planet.
   c. toward the planet.
   d. None of the above

7. Is this statement correct? “The gravitational force acting on any object is directly proportional to it mass.”
    a. Yes
    b. No
    c. Depends on the G constant
    d. None of the above
8. Assume that object 2 is positioned between objects 1 and 3 in free space. All three objects are aligned and the distances between them are the same. If objects 2 moves closer to object 1, it means that
    a. object 1 has a greater mass than object 3.
    b. object 3 has a greater mass than object 1.
    c. object 2 has the greatest mass.
    d. None of the above
9. When the distance between 2 objects doubles, the gravitational force between them
    a. reduces by half.
    b. doubles.
    c. does not change.
    d. None of the above
10. Assume that object 1 is on top of the highest mountain and object 2 is at sea level. Which one of the two objects experiences a greater gravitational force?
    a. Object 1
    b. Object 2
    c. Object 1 and object 2 experience the same gravitational force
    d. None of the above

Appendix G: Exit Interview Questions for Dissertation Study

1. Did you learn something new about physics from this learning experience? Please explain.
2. Did this learning experience change what you already knew about physics? Please explain.
3. Which part of this experience is the most useful in helping you learn about physics? Please explain
4. If you were asked to teach these concepts to your classmate, how will you teach them?